TagID generation and detection of Chipless RFID system

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Abstract— **The cost and non-planar structure of the existing chipped RFID system make them incomparable with the cheaper barcode identification system. In the last few years, several novel contributions to research on chipless RFID system are done making them a potential candidate to replace barcodes. The ID generation in the chipless tag is completely different from the chipped tag and this paper analyses the various methods of producing tag ID in absence of chip. The data capacity is the crucial part of any identification system and effective ways of increasing data capacity using multiple dimension are explored in this paper. Also, printing technology and parameters affecting printed tags are inspected. The next challenging phase of the chipless RFID system is the reading and decoding of the tag ID. The reader system consists of an RF section and a digital section. In this paper, the detection algorithms used in the digital section discourses. This study explores through the important phases of a chipless RFID system which still needs development and the findings can be incorporated to improve the reliability of the chipless RFID system to make this technology suitable for commercial applications.**

Index Terms*—*Chipless RFID, printed tag, Hilbert transform (HT), Signal space representation (SSR), Matrix pencil method (MPM), Continuous wavelet transform (CWT), Maximum likelihood (ML), Moving average filtering

I. INTRODUCTION

RFID (Radio Frequency Identification System) has emerged as an efficient wireless data transmission and reception technique for automatic identification and data capture. The basic RFID solution contains tag and reader as shown in Fig 1. RFID tags attached to the items modulates the signal received from a reader and sends back the encoded signal to the reader. The reader decodes the ID of the tagged item and updates the tag ID in a reader control system/database for further processing.

In chipped RFID system, the tag contains tag chips or integrated circuits (ICs) and tag antennas. Tag chip contains memory which stores the product's electronic product code (EPC) and other information so that it can be read and tracked by other RFID readers. The cost of this RFID system based on the chipped tag is mainly dominated by the cost of the silicon chip, thus stimulating research to create chipless identification tags. Another significant advantage of the chipless tag is their planar structure making them printable and thus reducing the cost of the tag to few cents. The passive chipless tags do not have any lumped components. So, less power is needed to transmit by the reader for the same reading range compared to chipped tags as they do not need extra power to turn on its lumped components as in the case of chipped tags. In chipless RFID system, the backscattered signal obtained from the chipless tag is processed to recognize and trace the tag ID. The chipless RFID tags act like a radar target having a particular frequency or time signature.

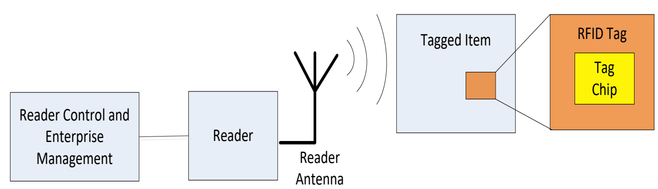

Fig 1: Block diagram of RFID system

The two vital component of chipless RFID technology is the tagID generation and tagID detection. The presented work does the comprehensive analysis of reported techniques for these two methods. Initially, the various methods of generating the identification code for the tagged object using the chipless tag is explained in section II. The chipless tag's efficiency is evaluated in terms of its spectral and spatial usage. The limitation in tag size, allowable frequency range limits the overall data capacity and a robust method for increasing the spectral and spatial efficiency using hybrid technology is also elaborated in this section. The chipless tag costing less than 1 cent can be obtained only by printing it with conductive materials. The different parameters affecting the performance of printed chipless tag is explained in Section III. The overview of different printing techniques suitable for printing of chipless tags and outcomes of printed tags in reported literature is shown in this section. The generated tag ID can be decoded using various algorithms.

In a chipless RFID system, the signal received by the reader antenna comprises of the backscattered signal from the chipless RFID tag located in the reader area, reflections from background objects (clutter) and noise. Therefore the detection process is a challenging phase of the chipless RFID system. In order to develop a detection algorithm, it is necessary to identify the features of the frequency signatures (the attenuations and phase jump introduced by the multi-resonating circuit). This identification is performed by the detector module in the RF section of the chipless RFID reader which compares the differences between the amplitude and gain between transmitted and received signal. This reading process helps to identify the peaks/no peaks from the information. The stored data is then processed in the digital control section of the reader. There are several decoding algorithms and de-noising techniques used in the signal processing of the digital section of the reader that reconstructs the frequency signatures of the chipless RFID tag. The detection can be performed based on the time-domain or frequency-domain response. Section IV gives a comparative analysis of the detection algorithms developed for chipless RFID tag detection.

II. Chipless Tag ID Generation

This section will explain different methods of generating tag identification number in chipless RFID system. The data encoding without the presence of the chip is challenging for researchers for designing the chipless tags as data handling the capacity of the tag is significantly reduced with the removal of the chip. Various techniques have been proposed in the literature for data encoding in the chipless tag. The data encoding of chipless tags can be based on Time Domain Reflectometry (TDR), Frequency signature, Image domain, and Phase domain.

A. Time-domain based tags

Chipless RFID tags based on time domain reflectometry generates a train of echoes with some delay in the time domain in response to an interrogation signal sent by the reader ref. [1].Generally, time domain reflections are caused by the presence of inductive or capacitive discontinuities or impedance mismatches and tag ID is extracted by analyzing the reflected echoes generated by those discontinuities. Data can be encoded either by on- off keying (OOK) or by using pulse position modulation (PPM) in time domain ref.[2].

One of the most known examples of a time domain reflectometry based chipless tag is the SAW tag which is based on surface acoustic waves (SAWs). It is the only commercially available chipless RFID tags and is developed by RFSAW. The encoding is done by estimating the time delays of the reflected SAW pulse. Various types of SAW tags are proposed in the literature. The SAW tag is excited by the chirp pulse in ref. [3], the tag containing few electrodes with the discussion of reflection, scattering, and transmission of the reflector is presented in ref. [4]. A multi-tone frequency-coded SAW tags are studied in ref. [5] and ref. [6] contains unidirectional interdigital transducer and 14 code reflectors. Delay line based time domain chipless tags operate by introducing a microstrip discontinuity after a section of the delay line. Microstrip transmission line is used as a delay line to generate the tag ID operating at 915 MHz in ref. [7].

Time domain RFIDs have a fast response compared to frequency domain RFIDs, and even though they require wideband circuits, they are particularly attractive due to their capability for fast signal processing in the time domain. However, their bit encoding capacity is low and hence the data density is also low. The bits are denoted by the reflected signal and to separate two-time positions so that the reflected signals do not overlap, the delay line is added between the discontinuities. We need to either increase the number of sections of delay lines or decrease the pulse width to increase the number of temporal positions. The increase in the number of delay line leads to a large-size tag, and also the signal amplitude decrease with the increase of length as each discontinuity generates a reflection of the interrogation pulse. A very short pulse is required for higher bit capacity and decreasing the pulse width is not easy to achieve in practice.

B. Frequency signature based chipless tags

The data encoding in spectral signature based chipless tags are performed in the frequency domain using resonant structures. The presence of resonance in predetermined frequency is identified as a data bit. Initially, RFID reader sends a multi-frequency interrogation signal to the RFID tag. Then the tag encodes its identity using a multi-resonating circuit which acts as a band-stop filtering of the interrogation signal and creates the spectral signature that can be decoded by the reader after being received. The resonator exhibits the frequency selective behavior and abrupt spectral features in amplitude spectrum, phase spectrum or/and group delay variation are used to encode digital data bits. Generally, one resonator corresponds to one data bit in these types of tags and 2^N combinations can be coded, where N is the number of resonators.

The frequency domain tags can be retransmission based or backscattered based tags. The multi-resonator tags based on retransmission are mainly composed by the transmitting (Tx), receiving (Rx) antennas and a multi resonating circuit. The transmitting and receiving antenna must be cross-polarized so as to limit the interference between the interrogation signal and the retransmitted encoded signal containing the spectral signature. The antennas are connected to the transmission line, and the resonators are either connected or coupled to this line. The retransmission based frequency domain tags have complex structures with a large size. The size reduction of retransmission based tags can be achieved by using resonators which can act as receiving antenna, filter and transmitting antenna. These backscattering based tags collect the RF signal, encode the tag ID and reflect back the encoded signal to the reader. The basic elements of the scatterer must generate the right electromagnetic signature in order to encode the identifier (ID).A direct link between the particular geometry and coding of ID must exist.

The commercial prospect of reported chipless tags can be assessed by using two figure of merit: Spectral efficiency and spatial efficiency. The spectral efficiency measures the efficient use of the given frequency band (bits/GHz) and spatial efficiency shows a number of bits that can be accommodated in given tag size (bits/cm^2). The unit cell resonator having Q factor or narrow bandwidth can encode the higher number of bits per GHz. In other hand, spectral efficiency increment is obtained by making a smaller resonator. Another popular method for slot resonator to obtain a higher number of bits in given area is by using slot length variation. Fig 2 shows the comparison of the spectral and spatial efficiency of some of the reported frequency domain tags. The spectral efficiency is seen higher for tags with antenna however, their bigger size make them spatially inefficient. Among the compared one, the u-slot resonator is highly efficient in terms of given frequency bandwidth usage. The tag size and available frequency bandwidth can be different for different application and by comparing the efficiency of tag in terms of its needed size and bandwidth usage, the appropriate tag can be chosen and modified as per the requirement.

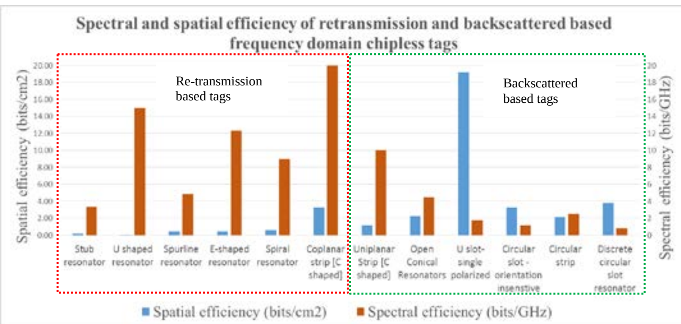

Fig 2: Spectral and spatial efficiency of frequency domain tags

C. Hybrid tags

The conventional method for increasing data capacity in frequency domain based tags is to increase the number of resonators where data encoding capacity becomes proportional to the tag size. The restriction in tag size, frequency range, and limitation in resonator Q factor, limit the data density. So, we need to consider alternatives to increase the data density on top of only tag modification. A combination of two or more domains can be utilized to create multi-domain based encoding system, instead of using a single domain for data encoding. This hybrid domain based system enables each elemental structure to encode more than one bit of information and consequently, the spectral and spatial efficiency in encoding information of chipless RFID system can be increased.

In tag designing, the output of the resonator at a certain domain (frequency, time, etc.) can be controlled by the certain dimension of the resonator (length, width, etc.). The hybrid tag will have the output in more than one dimension. The change in the value of one domain should not affect the value of other domain. For instance, if the encoding is based on RCS peak in the frequency domain and phase deviation , then the change in RCS peak in frequency domain should not affect the phase deviation and vice versa. Fig 3 (a) shows the constellation diagram when two dimensions ‘U’ and ‘V’ is used. If the single dimension is used, then the number of tagID for two states will be 2^n. However, when both the dimension ‘U’ and ‘V’ is used then the encoded data get increased to 2^{mn}. For ‘k’ states, the encoded tagID will be k^{mn} . The final tagID when two domain ‘U’ and ‘V’ is used can be constructed using Fig 3(b).

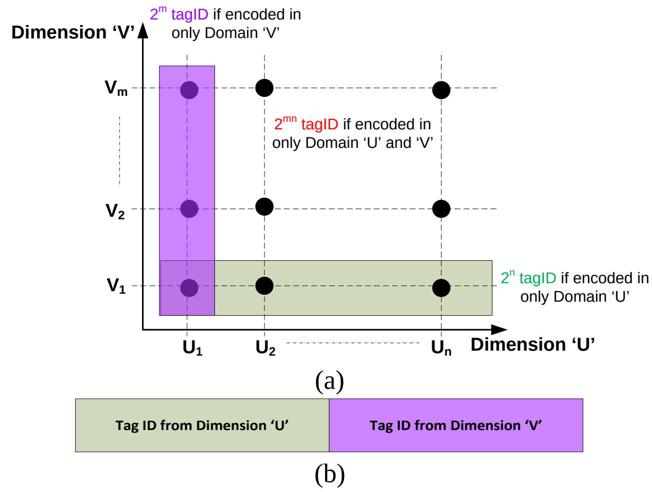

Fig 3: (a) Constellation diagram for hybrid encoding system (b) Coding Scheme for hybrid coding system

A hybrid domain tag based on resonant frequency and polarization angle is proposed in ref. [8] to increase the coding efficiency. When the E field of the interrogating plane wave is parallel to the split gap of the split ring resonator (SRR), a null is produced at the fundamental resonance frequency. So, depending on the polarization angle of the incident field, the EM response will have enough variation and data can be encoded in polarization dimension. A coding capacity of 22.9 bits is obtained for five resonators by combining phase deviation and frequency position encoding in ref. [9]. The slot length ‘L’ of the resonator can control the resonant frequency of the peak without affecting the phase deviation bandwidth and the separation between the two metallic strips has to control over the phase bandwidth. In this technique, larger frequency range was required and complex UWB reading system has to be designed for this purpose. The microstrip patch antennas loaded with open circuited high impedance stubs generated distinct phase characteristics in ref. [10]. The relative phase has been obtained from the phase difference between backscattered E-place and H-plane signals in the reader antenna. A unique code has been extracted with a 30° phase shift for 3 frequencies in ref. [10] developing phase-frequency based chipless tag. Similarly in ref. [11], the information has been encoded in the quantized values of the difference between the TE and TM phase response. The notch bandwidth and corresponding frequency position have been exploited in ref. [12] to encode 4 bits per single resonator. The coding elements dipole, rectangular ring, and rectangular patch generated three different notch bandwidth.

III. PRINTED CHIPLESS TAGS

Printing enables direct deposition of ink on the substrate opening the door of chipless RFID tag in many low-cost applications. This section presents a brief overview of commonly used printing methods and will report some of the printing techniques adopted in literature. Ref. [13] has described five printing techniques: flexography, offset lithography, ink-jet, screen print, and gravure print. Flexography prints the pattern printed on the areas raised above the non-image areas on the rubber plate. Offset printing is one of the widely used printing techniques in the newspaper industry. The inked image is transferred from a plate to a rubber blanket and from rubber blanket to the printing surface in offset printing. Ink-jet is most established and straightforward printing technique. This printing technique is efficient in terms of material usage as only desired material are deposited. The ink-jet can be of continuous ink-jet or drop on demand type. Screen printing uses a mesh to transfer ink to the substrate. The stencil contains the design and the ink is only transferred in the areas which are made permeable to the ink. In gravure printing, an image is etched on the cylinder which is rolled over a moving substrate and ink is transferred to the substrate. Gravure printing is considered to have high throughput, long print runs, uniformity, and versatility. The essential requirement for printed RFID tags in terms of accuracy, resolution, conductivity, thickness, and longevity is presented in ref. [13]. The conductive ink is required for printing functional RFID tags. The conductive inks can be water based or solvent based ink. The conductive ink contains conductive metal (pigment), a binder which keeps the pigment particles together, a solvent for pigment dispersion, and additives for adhesion as major constituents. The pigment determines the conductivity of the ink and usually, silver-based inks tend to provide higher conductivity ref. [14]. The conductive ink can be metal-based nanoparticle inks or can contain metal flakes.

A. Ink-Jet printed Chipless tags

Ink-jet printed chipless tag has been presented in ref. [15]. The linearly tapered antenna and bowtie tag antennas have been printed using inkjet printing process. The influence of printing process on the produced antennas has been analyzed to ensure the reliability and repeatability of the antenna performances. The time domain tags adopting uniform microstrip line (UML) and linearly tapered microstrip line (TML) has been printed on photo paper using Dimatrix inkjet printer and Cabot nano silver ink in ref. [16]. The printed patterns have been sintered in a convection oven at 100°C for 30 minutes. The UML tag was not readable, however, linearly tapered ML (TML) overcome the limitation of ink-jet printing technique and provided excellent readability. The investigation on printing LC resonator based chipless tag on packaging paper substrates such as CosmaPrint gloss, Terraprint gloss, Terraprint silk, and Cosmaprint silk has been presented in ref. [17]. The paper roughness has been decreased using overprinting to increase conductivity and ID codes were clearly recognized. Tag based on dual-rhombic loop resonators has been ink-jet printed on a polyimide substrate in ref. [18] . The silver nano particle based ink has been combined with CNT-doped organic resistive ink to implement a novel coding technique. A resistive strip created using organic ink to short the dual-rhombic scatterer in the middle generates peak magnitude. This organic ink is quasi-transparent and makes tagID detection difficult through visual inspection. So, this interesting behavior can be used for anti-counterfeiting applications. However, in this design, the large strip width has been used to compensate conductivity losses.

B. Screen printed Chipless tags

A 4-bit chipless tag based on planar resonance loop were printed on PET foil substrates using screen printing in ref. [19]. However, the printed pattern had higher resistance and particular resonance frequencies are not measurable. A square-shaped chipless tag is printed using screen printing on PET and paper substrates in ref. [20]. A slight shift of frequency was seen in between PET and paper substrate which corresponds to the increase in permittivity of the paper with respect to PET. Another 3-bit tag has been printed using silver based ink Dupont 5028 through screen printing ref. [21] . The silver content of the ink was 69-71% that lead to high conductivity. As mentioned in the paper, the reason for selecting screen printing was fast mass printing, no waste of expensive inks and to realize thick layers of up to 10 microns. The 10 microns thickness was obtained by using 280 mesh and ink was dried at 130°C for 5 minutes. The mean sheet resistance of the printed lines as in a range of 67 ± 1 mΩ/sq.

C. Flexography printed Chipless tags

A chipless tag has been realized on a paper substrate (Cardboard and glossy paper) using flexography technique in ref. [22]. The higher the anilox volume, higher will be the conductivity and higher quantity of ink. Various anilox rolls were investigated to find the best compromise between ink conductivity and cost and eventually 20 cm3/m was considered. The dried thickness was close to 5μm with this anilox and obtained conductivity was 3x105 S/m. The cliché pressure plays an important role in flexography. The insufficient ink leads to lower conductivity and excessive pressure results in pattern deformation. The tag with 20 resonators etched on the FR4 substrate, printed on PET on inkjet catalyst and realized on 20 μm paper by flexography was compared and widening of the resonance peaks were observed in the case of paper substrate overlapping the adjacent resonant modes which make this tag not usable. However, the electromagnetic signature was detectable for 5-bit tag printed on paper. A new resonator was designed considering the limitation of the paper substrate and flexography printing technique. The width was enlarged to increase the conductivity and three gaps were used to increase the selectivity of the resonator.

D. Effect of different parameters on printed tag

The analysis on the effect of different parameters related to printing affecting tag performance builds a firm understanding and practical insight on implementing conductive ink printed chipless RFID tag. The main parameters affecting the printed tags are the ink parameters, printing parameters, substrate characteristics, and design parameters. The ink parameters include conductivity, sheet resistivity, the solid content of the conductive material, ink type (water based/ solvent based) sintering temperature, sintering time and viscosity. The printing parameters like printing line resolution (dots per inch) and printing speed will depend on the printing technique. The substrate electrical properties such as dielectric permittivity, loss tangent, and substrate height are the major substrate characteristics affecting microwave performance of the tag. The substrate physical characteristics can also limit the sintering temperature and time. The printing technique can have a limitation on design parameters of the tag such as line width and gap width. Also, the thickness of ink deposited on the substrate is a vital issue as thickness significantly affects the conductivity.

A study on the effect of ink conductivity and substrate electrical properties such as permittivity and loss tangent on RF performance has been done for a dual polarized chipless tag in ref. [23]. It is seen that with the decrease of conductivity, resonant bandwidth increases, the depth of the frequency notch decreases and frequency is shifted slightly. The decrement of permittivity (ε_r) increased the resonant bandwidth, the attenuation at resonance and the resonant frequency. The loss tangent ($\tan\delta$) of the substrate also has a substantial effect on the tag performance. The most significant effect is seen in the notch depth which is attenuated by 35 dB at $\tan\delta=0.002$ to 10 dB at $\tan\delta=0.1$. So, a substrate with lower loss tangent is desirable to achieve higher notch depth. Similarly in ref. [22], it is seen that a conductive value varying from 3×10^6 S/m to 3×10^5 S/m caused 3 dB losses on the EM response and variation of thickness caused around 1 dB RCS variation and frequency shift of 200MHz for a highest resonant mode for the mentioned tag.

IV. TAG DETECTION

The chipless RFID reader extracts the backscattered signal and decodes the tag ID. The signal collides with other scatterers or tags which give a 'clutter' signal with interference. A number of detection techniques have been applied to achieve an accurate result of its tag ID. The detection techniques can be further divided into two sections which are the decoding of the frequency signature of the tag and de-noising the received signal.

A. Decoding & Denoising Techniques

The basic decoding technique is based on comparing the received data with threshold values obtained by calibration. This is, therefore, a basic approach and it does not possess the flexibility and adaptability required in the detection process to address errors due to a dynamic environment.

i. *Hilbert Transform*

Hilbert Transform (HT), has been used in reader development in the year 2012 ref. [24]. Hilbert transform (HT) is a complex analytical signal processing technique.

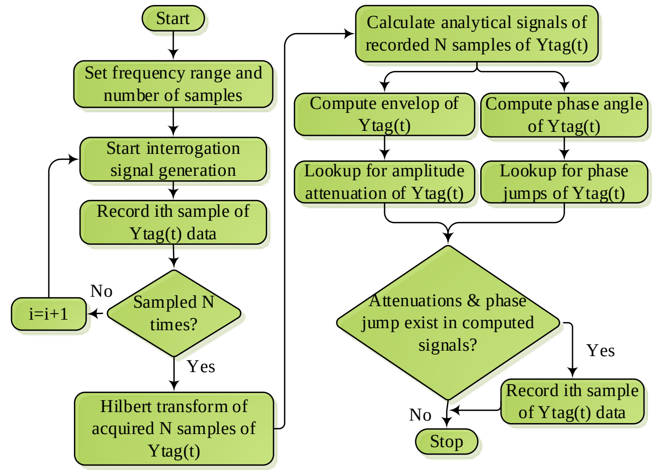

Fig 4: Flow chart of the signal processing using Hilbert Transform

This technique has been used to reconstruct the frequency signatures of the chipless tags. The flow chart of the signal processing of the HT is shown in Fig 1. It has been experimentally proven that HT provides the extraction of the amplitude and phase functions of the frequency signature.

ii. *Moving Average Technique*

Moving average technique is a simple de-noising technique which removes noises by acting as a low pass filter. In ref. [25], an eleven sample averaging moving average filtering has been successfully implemented on a low-cost mid-range microcontroller having low processing power capabilities and a smoothened waveform is resulted after using this filtering technique.

iii. *Signal Space Representation (SSR)*

The signal space representation of chipless RFID tags uses an efficient mathematical model to decode information in a chipless RFID tag. In ref. [26, 27], the frequency signatures are represented by a matrix which is composed of orthonormal column vectors and a singular value matrix. The constellation of signal points is plotted with a basis function as shown in Fig 2. It can be seen that as the number of bits increase this method will face limitations.

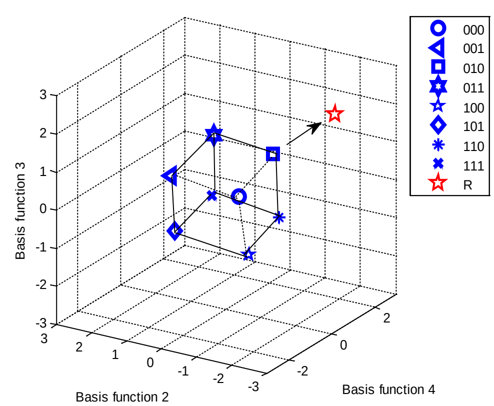

Fig 5: Reconstructed frequency signature plotted in the three-dimensional signal space as a point R.

iv. Continuous Wavelet Transform (CWT)

The approach of wavelet transform in the time-frequency analysis of the backscattered signal of the tag is another detection technique ref. [28]. The Gaussian wavelet has been used as the mother wavelet in this application. It gives the turn on times and the resonant frequencies of the signal and the wavelet coefficients provide significant information of the tag. The continuous wavelet transform acts as a matched filter. This technique can be used for both decoding and de-noising purposes.

v. Matrix Pencil Method (MPM)

Matrix pencil method (MPM) and Short time matrix principle method (STMPM) are two more detection techniques that have been applied for chipless RFID systems ref. [29]. These two techniques are applied in the time domain and are mentioned as accurate detection techniques in extracting the carrier to noise ratio (CNR) of the response. Detection is performed by extracting the poles and residues from the backscattered signal using the Matrix Pencil Algorithm. By using the matrix pencil algorithm it is possible to extract both the resonant frequencies and the rates of decay or the damping coefficients associated with the received tag backscattered signals given by (1).

$$y(t) = \sum_{i=1}^{P} a_i e^{-\sigma_i t} \cos(\omega_i t + \emptyset_i) + n(t) = \sum_{i=1}^{M} R_i e^{s_i t} + n(t) \qquad (1)$$

where, $a_i$and $\emptyset_i$are the amplitude and phase, $\sigma_i$is the damping factor, $\omega_i$is the angular frequency of the *i*-th damped sinusoid, *P* is the number of sinusoids, $s_i = -\sigma_i + j\omega_i$ are the poles of the signal,R_i are the complex amplitudes or residues associated with each pole, *M* = 2*P* is the number of poles, and *n(t)*is the additive noise contaminating the signal.

vi. Maximum Likelihood based detection (ML)

A Maximum Likelihood (ML) based tag detection technique and Trellis decoding technique has been developed in ref. [30] where detection error rate is compared with a bit to bit detection. It has been found that ML detection has the best performance. It reports that the computational complexity is higher in ML detection technique than Trellis detection technique.

vii. Adaptive Direct Path Cancellation

In this technique to cancel the clutter signal, a weighted direct path interference signal is subtracted from the received target signal, based on the least mean square (LMS) error algorithm. For a reference signal *v*, and a target signal *u*, the weighted vector can be derived by (2).

$$w = \frac{\langle v^H . u \rangle}{\|v\|^2} = \frac{\sum_{k=1}^{N} v(k)^* . u(k)}{\sum_{k=1}^{N} |v(k)|^2} \qquad (2)$$

The fast Fourier transform (FFT) function is used to convert the original signal into range domain where the direct path interference signal and target signal can be viewed and isolated ref. [31]. Then by applying the adaptive direct path cancellation, the target signal is obtained in the range domain. The adaptive direct path/clutter cancellation method has identified the tag frequency signatures with simulation and measurement results.

V. Conclusion

Chipless RFID will dominate the RFID market in the near future. This paper presents a comprehensive overview and analysis of the recent developments in tag designing, printing and signal processing aspects for chipless RFID systems.

The objective of tag design for chipless RFID system is mainly focused on increasing spectral efficiency and spatial efficiency. Time domain tags have the greater reading range and have fast response. However, their bit encoding capacity is low compared to frequency domain tags and only a few of them are printable. So, frequency domain tags are highly applicable to obtain high data density. However, the limitation in resonator's Q factor and size limits the data capacity which encourages designers to go for hybrid domain encoding. The single layer tags are printable and various parameters affecting the printed tags are explained in this paper.

The raw data received from the RF receiver of the system needs to be processed and denoised. The detection algorithm can be applied in the frequency domain, time domain, time-frequency domain or range domain. The presented decoding and denoising techniques differ according to their mathematical complexity, the requirement of a template signal in advance, noise characterization and the limitations in retrieving all tag information. Future directions based on this analysis can be the development of optimal detection methods to detect the tag signatures based on the total noise characteristics.

This attempt of reviewing tag ID generation and detection for chipless RFID technology will be helpful for researchers who are interested in developing novel tags and detection algorithm.

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