mm-Wave Letter-Based chipless RFID Tags on Cheap Plastic Substrates

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***Abstract*— In this paper, a novel design method for chipless RFID tags in frequency domain has been introduced. The tags are designed based on letters and symbols, and printed on the cheap substrates, such as plastic and paper. These tags are part of a bigger system which uses Artificial Intelligence for decoding. This paper demonstrates the way to adjust the dimensions of the letters so that desired backscatter frequency response can be achieved. This work makes the implementation of cheap and flexible tags easier for the IoT application in the mm-wave band.**

***Keywords*— Alphanumeric Tags, Chipless RFID, Plastic Substrate, mm-wave band, Pattern Recognition, Artificial Intelligence, IoT**

I. Introduction

RFID is a barcode complementary technology which does not have the line of sight limitation. There are two types of the tags in the RFID domain, chipped and chipless. The chipped tags have active elements inside. The chipless tags are simply a piece of metal with no intelligence. Chipless tags therefore should be designed in a way to have enough backscatter signal (enabling them to be detected) and encode the enough data. There are three main categories for chipless RFID tags, namely, time domain, frequency domain and spatial (image-based) domain.

Time domain tags need to make delayed echos to the interrogated wave, so that the reader is able to decode their contents. As the response from the tag is almost immediate, SAW substrates must be used to convert the incoming electromagnetic wave to acoustic waves. The acoustic waves then pass through the 1s and 0s discontinuities and make delayed pulse responses. The two limitations to this type of tag are that SAW substrates (which are made of piezoelectric materials) are expensive, and that the number of decoded bits are low unless a complex combination of modulation, channel capacity and reading distance is considered (maximum reported tag capacity is 100 bit tags in this case [1]).

Frequency domain tags are more widely used because of their simpler reader architecture. As the tag's signature is based on its null and peaks in the backscatter signal in the frequency domain, a Ultra-Wide Band (UWB) frequency interrogation is normally required as it can cover more bits. High data capacities of 19 bits/cm^2 [2], 35 bits per credit card size [3], 4.2 bits/cm^2 [4] are reported in the literature. The limitations are again tag substrate prices for appropriate substrates and low Q resonance bandwidths of the tags, which makes the final number of decoded bits low on the UWB spectrum[5].

Image-based tags are extension of time or frequency based ones, with added location information [6], [7]. The reported capacity for image-based polarized lines are 1.6 bits/cm^2 [6] and 2 bits/cm^2 [5]. Their limitations are the same for the other two types of the tag, namely, expensive substrate and low Q bandwidths.

There are four major considerations for designing chipless RFID tags in microwave and mm-wave, namely, using the cheap substrates with maximum backscatter (as the final tag should be detectable), making high data capacity (thus minimizing tag dimensions), making tag's reading orientation Independent and tag's flexibility. Conventional tags and the ones available in the literature can not achieve all of these requirements at once but involve a compromise between those.

This paper explains how the proposed letter tags overcome the common problems outlined above for the frequency and image-based types of the chipless tags.

II. Letter-based Tag Design

This paper is part of bigger project of using deep-learning and pattern-recognition methods for the decoding section of the chipless RFID systems. To train a data-hungry network, such as a deep-learner system, many tag samples are normally required. Using letter combinations as the tags provides the chance to produce as many different tag frequency response combinations as possible with very low cost. Current studies of the letter-based tags are mainly focus on implementing single letters only, with data encoding 3.1 bits/cm^2 [8] and 2.1bits/cm^2 [9]. Those proposed tags are not expandable easily, are not reading orientation independent and can not be printed on low cost materials like Mylar polyester films[10]. Their operating frequency is normally in the C-band of 3-10 GHz.

Firstly the two main considerations in the design of the chipless tags, namely the maximum backscatter on a cheap substrate and the maximum encoding capacity are discussed.

A. *Considering the reflectivity of non-microwave substrates*

For tags to be detectable, there should be enough structural mode reflections available once an interrogation signal hits the tag's surface. In other words, for the best results in frequency/image-based domains, the tag's substrate has to have minimum absorption of the interrogation signal and the highest possible reflectivity index.

The reflectivity of electromagnetic energy of a single-layer substrate as a function of frequency can be calculated using the following equation[11]:

$$R(dB) = \left| 20log_{10}\frac{jAtan(kd)-1}{jAtan(kd)+1} \right| \tag{1}$$

where

$$A = \sqrt{\frac{\mu}{\epsilon}},\ k = \frac{2\pi f}{c},\ \ j = \sqrt{-1}$$

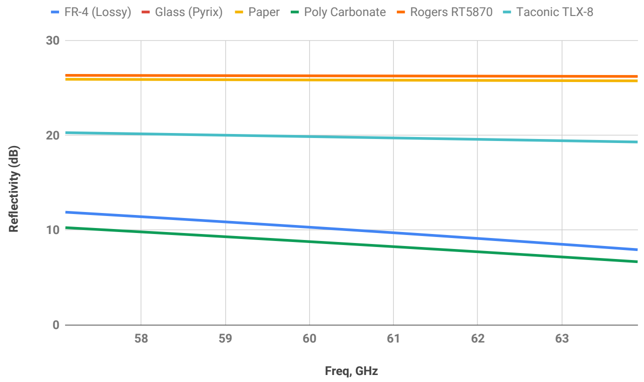

Fig. 1. Reflectively comparison chart for the substrates used

and μ and ϵ are the complex permeability and permittivity of the material respectively, k is the wave number, f is the frequency of the incident electromagnetic wave, c is the speed of light in a vacuum, and d is the thickness of the absorbing layer. The permeability and permittivity might also be functions of the frequency. Based on (1), Fig. 1 shows a comparison between the reflectivity of a few materials used in this research. The non-professional mm-wave substrates, like ploy-carbonate, paper and FR-4, have lower reflectivity index, meaning that they are less suitable for the mm-wave applications. Therefore some techniques are needed to increase the reflection, or the RCS. This low reflection problem is addressed at the later stage of the work as reported in section II-C by using combinations of a few letters, and increasing the ink printing depth.

B. Considering tag's encoding capacity for an AI decoding system

One of the most important design consideration for chipless tags is their encoding capacity. In the frequency domain and image-based tags the Q-factor quality determines the possible encoded bits in the certain range of frequencies. The higher the Q-factor of nulls, the more bits can be encoded in any particular spectrum. As the tags in this study are based on the AI methods, the capacity concept comes to the point that how distinguishable a tag is from the other tags. Here the focus is more on the designing tags which have higher changes in their frequency response, thus have higher chance to be uniquely identified.

C. Designing tags based on alphabet

This section illustrates how letter tags using some flexible size building blocks provide the flexibility in both the tag resonant frequencies and the Q factor.

There are many ways to make alphanumerical tags, but one of the most structured one is Peyote beading alphabets [12]. The illustration in Fig. 2 shows the concept of the design for the Peyote alphabet. There letters are made of the small building blocks. Hereafter every building block is called a cliff. As said, the aim is to to make as many combinations possible for the tags as possible, as a requirement for training the networks. The tags are made in a mesh size of 11 by 7 cliffs. In this design the cliffs are chosen in the way that the tag fits in the 1 cm by 1 cm space. In the design, the space around every tags should also be considered, as the next letter might start right after the last cliff. Although the number of cliffs per tag is 11 by 7 as in Fig. 2, they are considered 22 by 14 in practice as some cliffs need to be placed in the middle of the other cliffs, and the space between them is 0.5 cliff size wide.

The designed tags have the characteristics listed below.

1) The tags are based on 30 mil$\times$ 30 mil (0.762 cm^2) cliffs. Each letter occupies 1 cm^2, considering the space between letters.
2) They have increased data capacity in comparison to other reported tags. This is because in each symbol position of 1 cm^2 space, at least 52 different alphabetical symbols (the upper and lower case alphabets) + 20 numbers/symbols can be placed. This results in a 72 symbols/cm^2 (almost 6 bits/cm^2) capacity, which is far greater than the encoding capacity of the existing reported tags.
3) The tags have components in both the x and y-planes. This make them more visible in cross-polarized readers. Having components in the x and y planes makes the tags less sensitive to orientation issues compared to meander-line image bar tags, as there is sufficient cross-polarization signal to guarantee detection in any direction.
4) In particular, any substrate can be used for the tags provided that the backscatter signal is large enough and the link budget condition is preserved.
5) The tags are less sensitive to printing imperfections because of the detection method used (AI).

III. Measuring the Tag's Response

To increase the RCS response, the tags in this research have 5 letters each. The size of the tag is 5-by-1 cm^2, which is almost the size of an optical barcode (Fig. 3). In the experiments, the following observations found. Firstly, the tag response is well above the noise level as the RCS is high. Secondly there is a 10 dB difference between the top peak and bottom null, which makes the tag response distinguishable. Thirdly, there are enough peaks and nulls and variations in the response, to decode the tag data contents with very high success rate. The place of the peaks and nulls can be adjusted based on the chosen letters and their size, as it will be shown later in the next section.

In Fig. 3 some of the experimental tag combinations are shown. As said, the restriction in this research is to use cheap, flexible and affordable substrates, which are realized using screen printing on plastic substrates. This Fig. shows screen printing using M-creative and Inktec inks. The same samples made with the FR-4 substrate too. Both in the simulations and the experiments, a cross-polarization reader configuration is

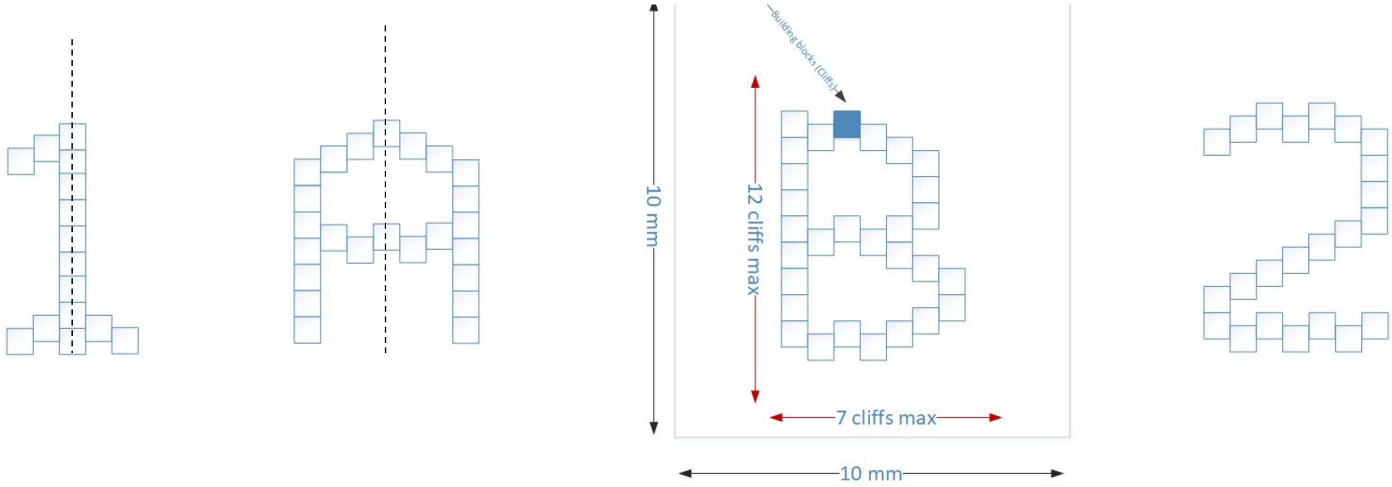

Fig. 2. Peyote Alphabet Design method, showing the building blocks (cliffs). The space between two letters are also considered in this design.

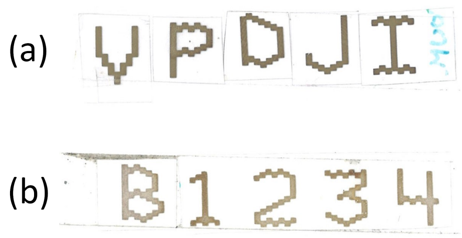

Fig. 3. Letter tags (combination of 5 letters) (a) screen printing on the Mylar polyester using Inktec ink; (b) screen printing on the Mylar substrate using M-creative ink.

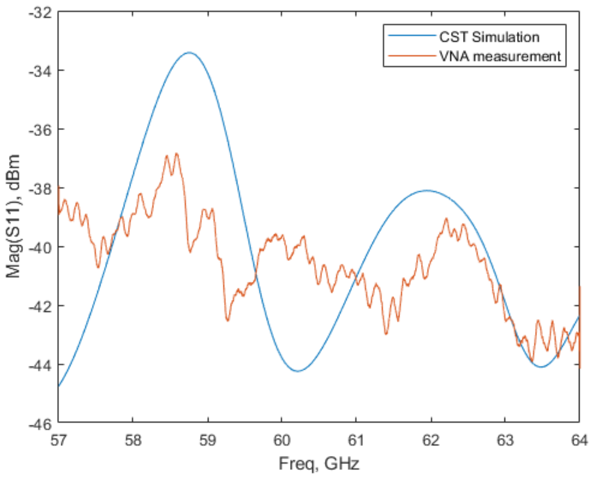

Fig. 4. CST and VNA responses of the tag ”56ZW3”

used in front of 5-letter tags. The simulation and experiment measurement comparison for a sample tag is shown in Fig. 4.

IV. Improving the Tag Design

As said, a set of 5 letters per tag has been chosen to increase the RCS response and to make the overall size the same as a normal barcode. But each letter has its own frequency response, which contributes to the overall response of the tag. Improving the tag response means being able to adjust peaks and nulls frequency and magnitude in the final frequency response. The first step in optimizing the frequency response is enhancing the individual letters in the way that their influence on the overall 5-letter tag can be improved. To satisfy this, a few simulations are carried on. Here each letter initially is characterized, and then its frequency response is improved by adjusting its cliffs. Initially the focus is on how to increase the peaks/nulls by optimizing the size of cliffs in every letter.

Fig. 5 shows the effect of changing cliff size in the RCS for the letter ”W”. Due to the space limitations, the other letters' results are not shown here. A sweep of 20 steps is done from 0.1 mm to 2 mm in the cliff size, and the effect of the cliff size vs location of the peaks and nulls in the frequency response is shown. It is easily seen that a peak at the 57.504 GHz with a value of -18.91 dBm can happen for letter ”W” if the size of its cliffs are chosen to be 0.2 mm. Similarly, if the size of 0.8 mm for the cliff size is chosen, there will be a null at 58.491 GHz with the depth of -68.91 dBm.

Based on the findings in Fig. 5 and similar graphs for other letters, a configuration can be found to optimize the effect of every letter in the final 5-tag combination. In the larger scale, once this experiment is done on all of the letters, a simple program is used to determine the cliff size for each letter, to maximize the efficiency of nulls and peaks placements in the frequency spectrum.

V. Conclusions

Based on the research presented in this paper, it appears that letter-based chipless tags screen printed on the plastic substrate are of great value, as they are cheap and flexible enough to be used like a hidden barcode. The problems are that they do not have enough backscatter reflections to be detected effectively, they are not symmetric in their design to be orientation independent, and their frequency response is difficult to be adjusted for peaks and nulls locations.

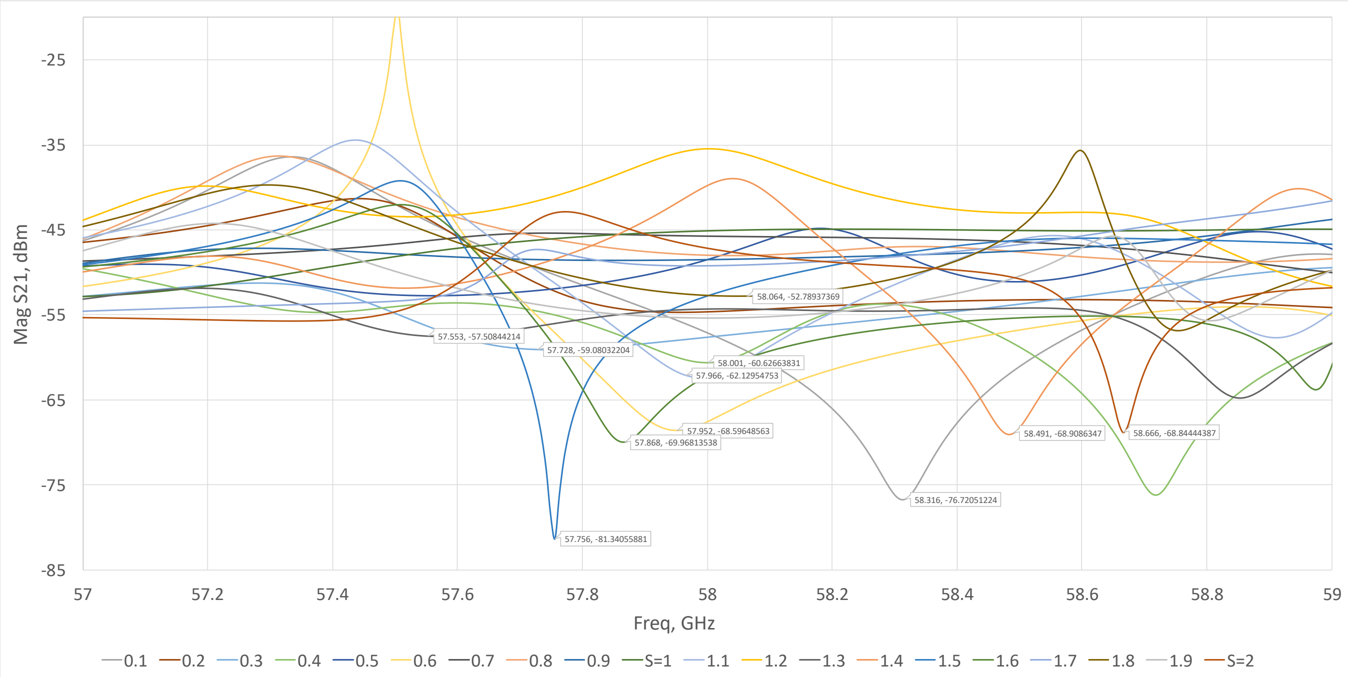

Fig. 5. Tag RCS response, using different building blocks for letter W.

In this paper these main problems were illustrated and possible solutions proposed briefly. For enough backscattering, five letters was used to represent one tag, instead of one single letter. This increased the total RCS (detectivity) and also unfolded encoding capability, as every letter in the tag can have 72 different symbols (resulting in 6 bits/cm$\hat{2}$).

As the system is based on AI, it will be shown in the coming papers that the rotated tags can still be detectable to some degrees. This is inherent to the nature of the intelligence added to the detection algorithm, similar to the human brain which can still read the letters correctly if they are rotated. This provides some robustness for the tag reading direction errors.

To address the adjustment of the frequency response, a few simulations were conducted to tune the size of the cliffs. It was shown that with adequate size of the cliffs in each letter, particular frequency peaks and nulls could be achieved. Although the letter frequency responses interfere with each other, if the nulls and peaks were separated enough, the overall response of the tag could be well adjustable.

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References

[1] M. Pöpperl, A. Parr, C. Mandel, R. Jakoby, and M. Vossiek, "Potential and practical limits of time-domain reflectometry chipless RFID," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 9, pp. 2968–2976, 2016.

[2] A. Vena, E. Perret, and S. Tedjini, "High-Capacity Chipless RFID Tag Insensitive to the Polarization," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 10, pp. 4509–4515, 2012.

[3] S. Preradovic, I. Balbin, N. C. Karmakar, and G. F. Swiegers, "Multiresonator-based chipless RFID system for low-cost item tracking," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 5, pp. 1411–1419, 2009.

[4] R. Rezaiesarlak and M. Manteghi, "Complex-natural-resonance-based design of chipless RFID tag for high-density data," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 2, pp. 898–904, 2013.

[5] D. H. Nguyen, M. Zomorrodi, and N. C. Karmakar, "Spatial-Based Chipless RFID System," *IEEE Journal of Radio Frequency Identification*, vol. 3, no. 1, pp. 46–55, 2019.

[6] S. Kofman, Y. Meerfeld, M. Sandler, S. Dukler, and V. Alchanatis, "Radio frequency identification system and data reading method," 5 2012.

[7] M. G. Pettus, "RFID system utilizing parametric reflective technology," 12 2008.

[8] S. Tedjini, O. Boularess, T. Andriamiharivolamena, H. Rmili, and T. Aguili, "A novel design of chipless RFID tags based on alphabets," in *Microwave Symposium (IMS), 2017 IEEE MTT-S International*. IEEE, 2017, pp. 1561–1563.

[9] O. Boularess, H. Rmili, T. Aguili, and S. Tedjini, "Analysis of electromagnetic signature of Arabic alphabet as RF elementary coding particles," *Wireless Power Transfer*, vol. 2, no. 2, pp. 97–106, 2015.

[10] L. M. Arjomandi and N. C. Karmakar, "An Enhanced Chipless RFID System in 60 GHz Using Pattern Recognition Techniques," in *2018 48th European Microwave Conference (EuMC)*, 2018, pp. 973–976.

[11] L. d. C. Folgueras, M. A. Alves, and M. C. Rezende, "Dielectric properties of microwave absorbing sheets produced with silicone and polyaniline," *Materials Research*, vol. 13, no. 2, pp. 197–201, 2010.

[12] S. Kerrigan, "Peyote Alphabet Pattern," 2015. [Online]. Available: http://www.bellaonline.com/articles/art42985.asp accessed: Sep 23, 2019