July 2006

Space-Filling Curve RFID Tags

John McVay
Villanova University

Ahmad Hoorfar
Villanova University

Nader Engheta
University of Pennsylvania, engheta@ee.upenn.edu

Space-Filling Curve RFID Tags

Abstract

A completely passive Radio Frequency Tag is proposed, utilizing the scattering from electrically small but resonant inclusions. When placing these space-filling curve inclusions in an array and scaling each element within the array such that each element has its own separate resonant frequency, a radio frequency barcode can be developed from the Radar Cross Section of the array. The narrow bandwidth inherent to such inclusions can be helpful in packing the overall signature into a relatively small frequency spectrum. Such Radio Frequency Tags may have potential use in some applications of Radio Frequency Identification Systems.

Keywords

Compact Resonator, Radar Cross Section, Radio Frequency Identification (RFID), Radio Frequency Tag (RFTAG), Space Filling Curves

Comments

Space-Filling Curve RFID Tags

John McVay *(1), Ahmad Hoorfar (1) and Nader Engheta (2)

(1) Department of Electrical and Computer Engineering, Villanova University, Villanova, PA 19085, USA

(2) Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, PA, 19104, USA

***Abstract* — A completely passive Radio Frequency Tag is proposed, utilizing the scattering from electrically small but resonant inclusions. When placing these space-filling curve inclusions in an array and scaling each element within the array such that each element has its own separate resonant frequency, a radio frequency barcode can be developed from the Radar Cross Section of the array. The narrow bandwidth inherent to such inclusions can be helpful in packing the overall signature into a relatively small frequency spectrum. Such Radio Frequency Tags may have potential use in some applications of Radio Frequency Identification systems.**

***Index Terms* — Compact Resonator, Radar Cross Section, Radio Frequency Identification (RFID), Radio Frequency Tag (RFTAG), Space Filling Curves.**

I. INTRODUCTION

The ever increasing applications of Radio Frequency Identification (RFID) and Radio Frequency Tagging (RFTAG) for commercial inventory control in warehouses, supermarkets, hospitals as well as in military friend-and-foe identification have resulted in considerable interest in the design of low-cost, thin-film printed antennas and sensors. The current technology can be divided into two main groups, namely, passive and active RFTAG's. In general, both active and passive tags utilize integrated circuits, with active tags utilizing a source, such as a battery. Recently, we proposed the use of Hilbert and Peano space-filling curves in the design of completely passive RFID tags and presented some preliminary results [1]. In the present work, we investigate the characteristics of such tags in more detail, and in particular, analyze their performance in the presence of various tagged objects, both numerically and via measurements. In addition, we present techniques for reducing the polarization dependence of such tags.

II. HILBERT AND PEANO SPACE-FILLING CURVES

The first few iteration orders of Hilbert and Peano curves are shown in Figure 1 [2]. An interesting property of a space-filling curve is that, as the higher iteration-orders of this curve are considered, a long "line" can be compacted into a small "surface" area. From an electromagnetic point of view, such a curve, filling a small footprint, may provide a structure that can be resonant at a wavelength much longer than its footprint. Such a "compact resonator" can be quite useful in various applications in radiation and scattering problems. For instance, this feature is of interest to antenna designers since it provides a planar resonant radiator that can have a very small footprint as one considers the higher orders in iterative filling of a 2-D region [3-6]. These curves have also been used in the design of inclusions for forming high-impedance surfaces (i.e., artificial magnetic conductors) [7].

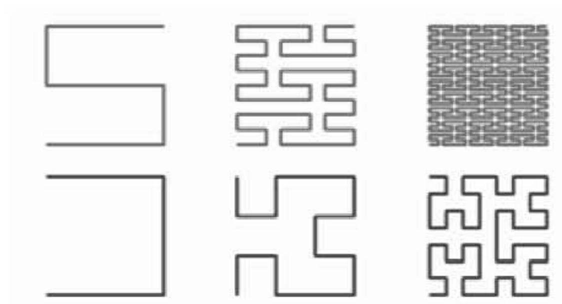

Fig. 1. First three orders of Peano (top) and Hilbert (bottom) space-filling curves.

III. RFID TAGS USING PEANO AND HILBERT CURVES

The "compact resonator" behavior of the Peano and Hilbert curves may allow for relatively small resonant passive tags with comparably large scattering characteristics. The relatively narrow bandwidth inherent to these geometries may prove useful in allocating the narrow resonances as the "spectral ID". Figure 2 shows the numerically simulated monostatic RCS of a planar conducting element patterned after the Peano curve of order 2, contained within a 30 mm x 30 mm footprint. Different peaks in the frequency response shown in Figure 2 correspond to the resonances of the Peano element when illuminated with a normally incident plane wave with an x- or y-polarized electric field. With respect to the resonant wavelength, the 30 mm-footprint dimensions containing the curve are just 0.07λ where λ is the wavelength at the first resonance, corresponding to the Ey excitation. The scattering pattern of this curve behaves like a y-directed dipole at its first fundamental resonance. To demonstrate a potential RFID application of the Peano-curve, a 5 element array of Peano curve elements of order 2, shown in Figure 3, was modeled using Method of Moments (MoM). Each element within the array is designed to have its first resonance at a separate and particular frequency. When illuminated with a normally incident y-polarized plane-wave, this geometry gives rise to the scattering shown in Figure 3. Multiple peaks in the Radar Cross Section (RCS) are evident and each peak corresponds to the first resonance of an element within the array. For this illustration, the array was designed to produce a monostatic RCS representative of the binary number 11111, where a peak in the RCS refers to a binary 1. In this manner, the frequency signature of scattering from the array could be considered as an RF-barcode. Similar results are obtained when an array of Hilbert curve elements is used. It is noteworthy that the footprint of the Peano or Hilbert array, with respect to the resonant wavelengths, can further be reduced by using curves of higher iteration orders.

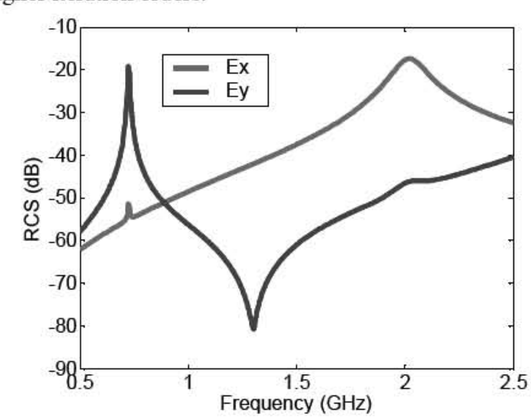

Fig. 2. The monostatic RCS of a 30mm x 30mm Peano-curve element of 2nd order.

A. RCS of Typical Inventory Object with SFC-Tag

To investigate the performance of the proposed space-filling RF tags when placed near a typical inventory object, we have numerically modeled, using Finite Element Method (FEM), the RCS of the 5 element array of Peano-curve elements of 2nd order on a paper roll (see Figure 4). The paper roll was given ε_r=2.6, tanδ=0.08 as appropriate values in [8]. The monostatic RCS results for paper rolls of various radii are plotted in Figure 4. One can clearly see the peaks corresponding to the resonant frequencies of the Peano curve elements. As the radius of the paper roll increases, however, the resonant peaks become less pronounced due to the increased contribution of the paper roll to the overall RCS of the combined geometry. Appropriate signal processing algorithms may potentially be used to enhance the peaks in the received RCS spectrum.

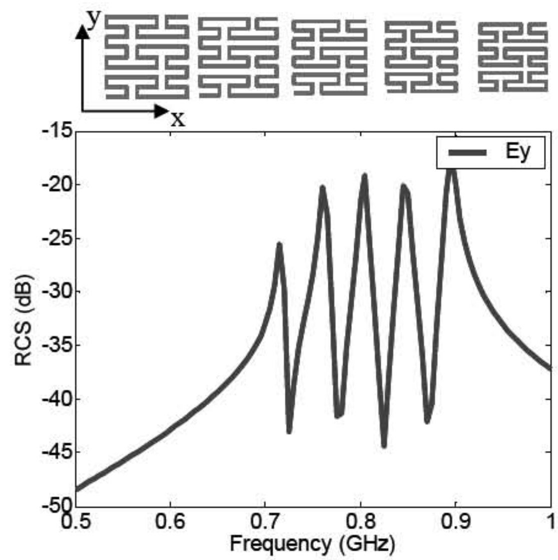

Fig. 3. An array of the 2nd order Peano-curve elements and its monostatic RCS frequency response. The total length of the array is about 163 mm.

IV. MEASUREMENT AND EXPERIMENTAL CONFIRMATION

In order to confirm the overall concept, 3-element arrays were fabricated, corresponding to the Peano order 2 and Hilbert order 3 geometries (see Figure 5). The arrays were fabricated on DUROID 5870 (ε_r=2.33) and measured in an anechoic chamber. The experimental set up consisted of two horns -- one transmit and one receive horn -- and a 30-cm-foam spacer to hold the RFID in the far-zone of the receive antenna. For both cases, the largest element in the array was given a 6.3mm footprint in order to put the lowest resonant frequency within the frequency range of relatively constant gain for the horn antennas utilized. The receive antenna, spacer and RFID are shown in Figure 5. In each case, a measurement was taken both in the presence of, and in the absence of the RFID such that background subtraction could be performed to obtain the frequency characteristics of the RFID's. The results of these measurements are shown in Figure 6 and for comparison, simulation results, utilizing MOM and FEM, are also shown. In the simulations, the bi-static RCS was collected 180° from the angle of incidence in order to correlate with the measurement set-up. The MOM simulations utilized a dielectric of infinite extent while the FEM case accounts for the finite substrate effects. The shifts in the resonances can be attributed to dimension inaccuracies in the fabrication process, which was done by hand, as well as possible uncertainties in the exact dielectric parameters.

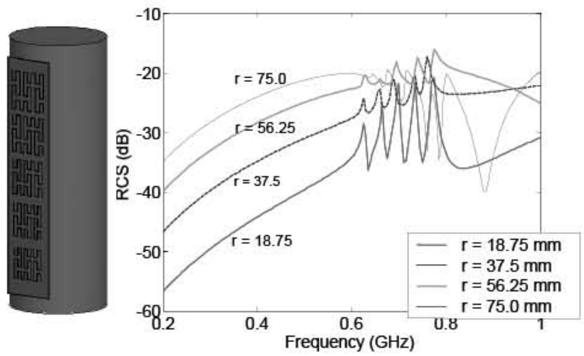

Fig. 4. The Peano-curve array placed on a paper roll of height 21 cm and radius r, and the RCS of the Peano-curve RF tag near a paper roll for the different radius values.

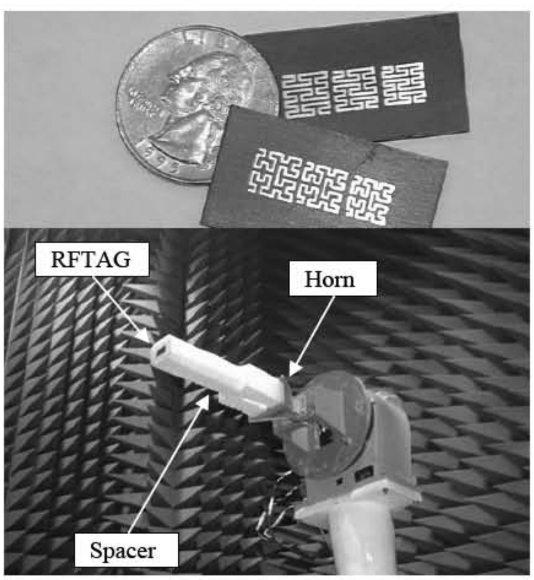

Fig. 5. Fabricated 3-element Peano and Hilbert Arrays (top) and the Measurement Set-up (bottom).

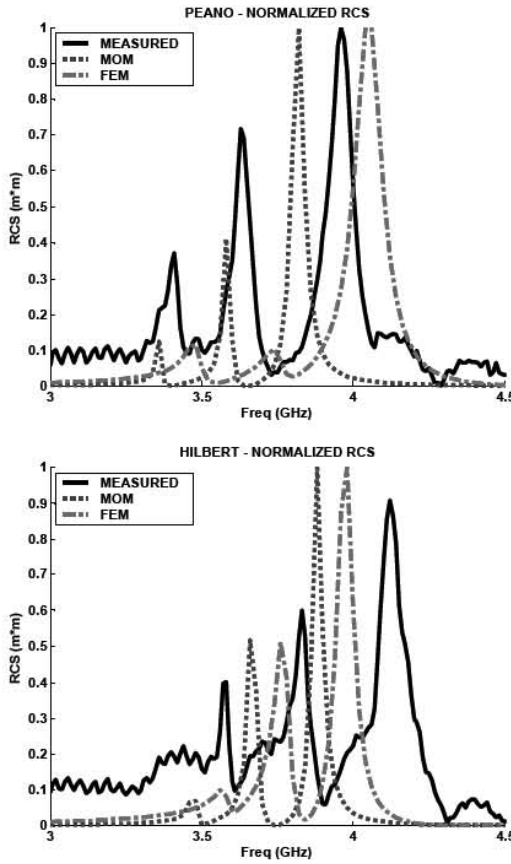

Fig. 6. Measurement and Simulation Results for the 3-Element Peano and Hilbert Arrays.

A. RCS Measurement of Typical Inventory Object with SFC-Tag

To investigate the performance of the proposed space-filling RFTAG's when placed near a typical inventory object, we have measured, the RCS of the 3-element arrays of Peano and Hilbert-curve elements, shown previously in Figure 5, on a paper roll. The measurement setup consisted of two horns with a 100cm separation distance between them. The tagged object, in this case a paper roll, was placed 122cm downrange. The paper roll had a height of 20cm and a diameter of 5.7cm and was placed on a foam pillar. The RCS was collected utilizing an Agilent E-5071B vector network analyzer and absorbing material was used to reduce noise and reflections within the room. Measurements were taken both in the absence of and in the presence of the RFTAG's in order to perform background subtraction. The RCS results are plotted in Figure 7, for both tags utilized. The peaks corresponding to the resonant frequencies, f1, f2 and f3, of the SFC curve elements can be seen.

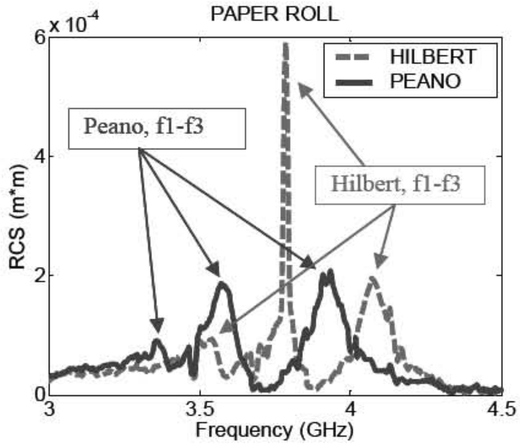

Fig. 7. Measurement Results for the 3-Element Peano and Hilbert Arrays on a Paper Roll.

V. Polarization Independent SFC-Tags

One potential solution to overcome the polarization dependencies of the Hilbert and Peano curves is the arrangement shown in Figure 8 [1]. In this configuration, shown here for the Hilbert curve, a sub-array consisting of multiple elements rotated 90° with respect to one another is used. In this manner the tags made of such sub-arrays may have multiple resonances independent of the polarization of the incident wave.

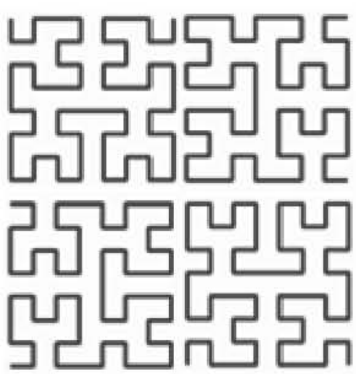

Fig. 8. A Sub-Array of Hilbert Elements of Order 3 used for Polarization Dependence Reduction.

VI. Conclusion

Arrays of Peano and Hilbert space-filling curve elements are proposed for potential use as RFID tags. It was shown that these electrically compact resonators could produce relatively large scattered fields over an inherently narrow frequency band at their corresponding fundamental resonant modes. Using both numerical simulations and RCS measurement we also investigated the performance of such RF tags when placed near a typical paper roll. The performances of Peano and Hilbert curve arrays near other common inventory objects are presently under investigation and will be given in the presentation. In addition, numerical and experimental results on the scattering performance of the polarization independent configuration shown in Figure 8 will be presented.

Acknowledgement

This work was supported in parts by the Office of Naval Research under Contract N65540-05-C-0028.

References

[1] J. McVay, N. Engheta and A. Hoorfar, "Radio Frequency Identification Utilizing Passive Space-Filling Curves," USNC-URSI National Radio Science Meeting, Washington D.C, July 2005.
[2] Hans Sagan, Space- Filling Curves, Springer- Verlag, 1994.
[3] K. J. Vinoy, K. A. Jose, V. K. Varadan and V. V. Varadan, "Hilbert curve fractal antenna: a small resonant antenna for VHF/UHF applications," Micrawave and Optical Technology Letters, Vol 29, No. 4, pp. 215-219, May 2001.
[4] J. Zhu, A. Hoorfar, N. Engheta, "Bandwidth, cross-polarization, and feed-point characteristics of matched Hilbert antennas," IEEE Antennas and Wireless Propagation Letters, Vol. 2, pp. 2-5, 2003.
[5] D. H. Werner and Suman Ganguly, "An Overview of Fractal Antenna Engineering Research," IEEE Antennas & Propagation Magazine, Vol. 45, No1, pp 38-56, February 2003.
[6] J. Zhu, A. Hoorfar, N. Engheta, "Peano antennas," IEEE Antennas and Wireless Propagation Letters, Vol. 3, pp. 71-74, 2004.
[7] J. McVay, N. Engheta, A. Hoorfar, "High-impedance metamaterial surfaces using Hilbert-curve inclusions," IEEE Microwave and Wireless Components Letters, Vol. 14, No. 3, pp. 130-132, March 2004.
[8] R. Olmi, M. Tedesco, C. Riminesi and A. Ignesti, "Thickness-independent measurement of the permittivity of thin samples in the X band," Measurement Science and Technology, Vol. 13, pp 503-509, 2002.