Additively Manufactured Triple-Band Fractal Antenna-on-Package for Ambient RF Energy Harvesting

Azamat Bakytbekov, Atif Shamim
(King Abdullah University of Science and Technology): Electrical Engineering Department, KAUST, Thuwal, Saudi Arabia,
Azamat.bakytbekov@kaust.edu.sa

***Abstract*— Billions of wireless sensing devices must be powered for Internet of Things (IoT) applications. Collecting energy from ambient RF spectrum to power sensor nodes is one of the possible solutions. In this work, we present an antenna for RF energy harvesting applications which operates at multiple bands and has been realized through additive manufacturing (combination of 3D and screen printing) on a package, thus optimizing the space and cost requirements. The antenna design utilizes the cantor fractal approach which enables it to operate at three frequencies (GSM900, GSM1800 and 3G at 2100MHz) simultaneously. Decent gain, triple-band performance, lower cost and compact size makes this antenna a promising candidate for ambient RF energy harvesting applications.**

***Index Terms*—Triple-band antenna, Cantor fractal antenna, additive manufacturing, system-on-package, 3D printing.**

I. Introduction

Power consumption of sensor nodes in IoT scenario is one of the main limitations. Ideally, they must be autonomous, self-powered and low cost. So, collecting RF energy from the ambient environment, from sources such as Wi-Fi, 3G, 4G LTE or GSM is an attractive solution for the future self-sustainable sensor nodes of IoT.

There are several key parameters for antennas to fit into IoT RF energy harvesting applications. Firstly, the antennas must be low cost (due to high volume); secondly, the size of the antennas must be small (for integration with sensors); and finally, it must be multiband (to boost collected power from several sources). The first two requirements can be met by utilizing a system-on-package approach where the antenna is implemented on the package of the circuits which is not typically the case as antennas are implemented on separate PCB. By utilizing the SoP concept, size and cost of the antenna can be reduced, and available space can be optimized. Cost of the antenna can be further reduced by using additive manufacturing techniques like 3D printing and screen printing. Finally, the multiband performance of the antenna can provide more power by collecting from several sources simultaneously and adding them up together.

Different antennas for RF energy harvesting applications have been published in the literature before [1, 2], but most of them focus on one frequency band only which limits the amount of collected power. Though there are few papers that show multiband performance [3, 4], techniques like 3D printing and SoP have not been used. Also, straightforward approaches like integrating several antennas together to achieve multiband performance have been presented in [5, 6] however this is not the best solution cost- and size-wise.

This paper presents the antenna for RF energy harvesting applications that meets all the IoT requirements stated above. Firstly, the antenna is triple-band. The operation bands are GSM900, GSM1800 and 3G at 2100MHz because they have the strongest power levels. Novel Cantor fractal approach is used to achieve triple-band performance of the antenna. SoP concept is used by placing the antenna on the outer five faces of the cube package. Cost of the antenna is minimized by using additive manufacturing techniques. In addition, cube box is fabricated through the 3D printing of plastic and the antenna is fabricated by screen printing of conductive silver paste. The work which shows the RF energy harvesting performance of the whole system is presented in [7].

II. Antenna Design

A. Concept of Fractals: Cantor Fractal

The term “fractal” originates from the Latin word “fractus”, which means “to break into pieces” [8]. The usefulness of the fractals in antenna design is that they can provide multiband or wideband performance due to the combination of different lengths. German mathematician Georg Cantor created a relatively simple form of fractal, which is known as Cantor fractal. The pattern of the Cantor fractal is as follows: the first line segment is copied, split up into three parts and the middle section is deleted. The same process is reiterated several times (Fig. 1a).

B. 3D Cube Antenna Optimization

The Cantor fractal antenna is designed using Ansys HFSS software. Fig. 1b illustrates the 2D planar version of the Cantor fractal antenna which was presented in [9]. The Cantor fractal antenna is fed by a 50 Ω microstrip line and has a semicircular ground plane. 3D cube antenna is the continuation work followed the 2D planar antenna.

As the RF energy harvester is a system containing several constituent elements such as an antenna and different circuits, it is useful approach to design the antenna on top of a package so that the package becomes functional part of the system. So, Cantor fractal antenna is wrapped around the sides of a cube box. The reason to choose Cantor fractal for this work is that it is much easier to fold Cantor fractal on a cube package compared to other fractals that have very complex shapes. Also, cube shape is chosen for a package because of its simple and symmetric structure. The dimensions of the cube box are 5x5x5cm^3. The Cantor fractal antenna is redesigned from monopole to dipole since it is hard to accommodate the large ground plane on the cube sides. The transformation is done by placing two monopole antennas as two arms of the dipole antenna as shown in Fig. 1c. Some structural changes on the Cantor structure have been made to accommodate the Cantor fractal dipole on the cube sides. Coplanar strip lines 2mm in width are used to feed the 50Ω antenna.

Analysis on the number of iterations has been conducted to determine the bandwidth dependence on the number of iterations. Fig. 2a-d present pictures of the cube antenna with one, two, three, and four iterations. Fig. 2e shows how different numbers of iterations change the impedance bandwidth of the antenna. This analysis indicates that 3D cube Cantor fractal antenna is multi-band and it will be designed with four iterations to focus on three frequencies of interest.

Further optimization is done on sensitive parts of the antenna structure to tune the antenna impedance at frequencies of operation. Current distribution on the antenna sur-face is plotted on HFSS to identify parts of the antenna structure that is the most sensitive to impedance tuning. Fig. 1d illustrates the current distribution of the antenna at principal frequencies. First, optimization of the width of rectangular segments W and the separation S have been performed. The total length of the antenna is restricted by the dimensions of the cube. Different combinations of W and S were simulated to find the optimal values. Three combinations were chosen such that W = 8mm, S = 8mm; W = 10mm, S = 6mm; W = 12mm, S = 4mm. Fig. 3 shows how each combination affects the impedance bandwidth of the antenna. Fig. 1d also shows that the transition regions from the rectangular segments to the separations have the highest currents. Therefore, widths of the separations need to be optimized. After the optimization process, it is established that the widths of the first, second, and third separations are 5.5mm, 0.33mm, and 0.86mm respectively.

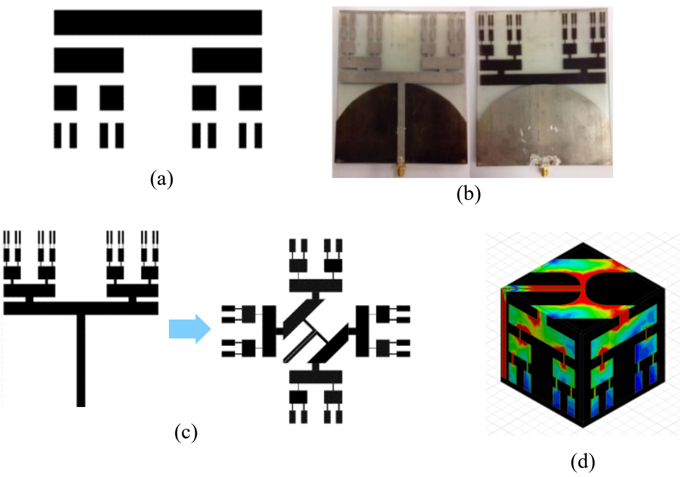


Fig. 1. (a) Cantor fractal (b) 2D planar version of the Cantor fractal antenna (c) Transformation from monopole to dipole (d) Current distribution at 900MHz

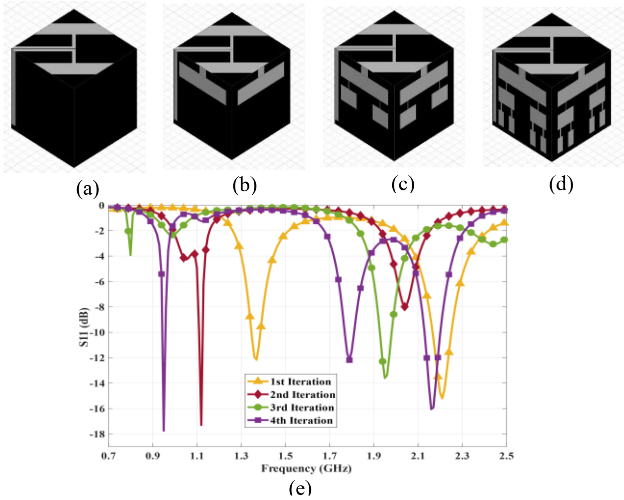


Fig. 2. Cube antenna with (a) one (b) two (c) three (d) four iterations (e) Effect of different iterations on antenna bandwidth

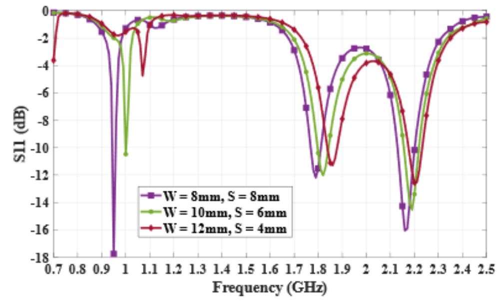
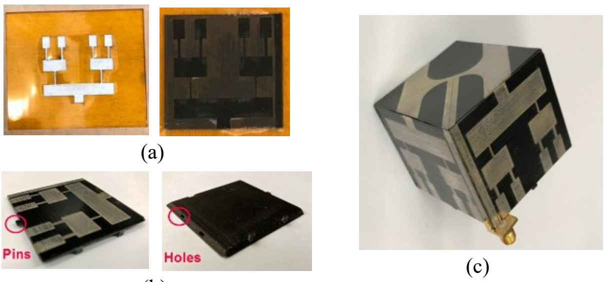


Fig. 3. Effect of W and S on the antenna bandwidth

III. FABRICATION

The use of 3D printed plastic substrate for the antenna design affords flexibility in terms of size, thickness, and structure of the cube. The fabrication process consists of two steps: the first is printing plastic substrate on a 3D printer and the second is metalizing the surface of the substrate based on the antenna structure. The Stratasys Objet 260 Connex 3D printer is used for printing of the plastic substrate. The dielectric plastic material is called Vero which has dielectric constant of 2.8 and loss tangent of 0.02. The thickness of the cube sides is 1mm. The metallizing technique is chosen to be screen printing due to the three reasons: elimination of skin depth issues, fast fabrication time, and relatively higher conductivity of silver paste compared to other printing techniques. Masks for screen printing are prepared using laser cutter and kapton tapes (Fig. 4a). The masks are placed onto the surface of the cube sides using the right alignment. After silver paste is applied, the samples are left inside the oven for 10 mins at 120 C. This makes the silver paste become solid and conductive. As each cube face is fabricated separately, they have pins and holes that will help to build the cube and hold the cube structure together (Fig. 4b). To achieve robust electrical connections between faces, conductive epoxy is applied on the edges of the cube. Fabricated cube antenna is shown in Fig. 4c.



(a) (b) (c)

Fig. 4. (a) Masks for screen printing (b) Pins and holes on cube sides (c) Fabricated cube antenna

IV. MEASUREMENT RESULTS

The reflection coefficient of the cube fractal antenna is demonstrated in Fig. 5. As it can be observed, measured and simulated results show good match between each other and the resonances are located around 900MHz, 1800MHz and 2100MHz frequencies. The gain of the antenna at three frequencies for simulation and measurement are illustrated in Table II. Consistent 1dB difference between simulated and measured results can be explained by the possible slight mismatch between silver paste conductivity and loss tangent of 3D printed dielectric used in simulation and their real values. Radiation patterns of the antenna at three frequencies of operation are shown in Fig. 6 and good agreement between simulation and measurement is achieved.

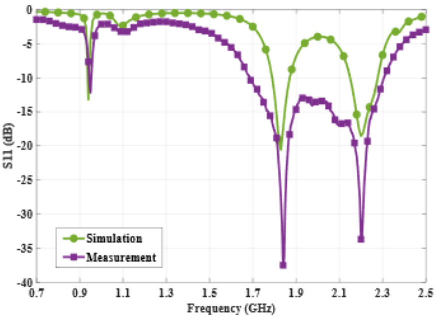


Fig. 5. Reflection coefficient of the antenna

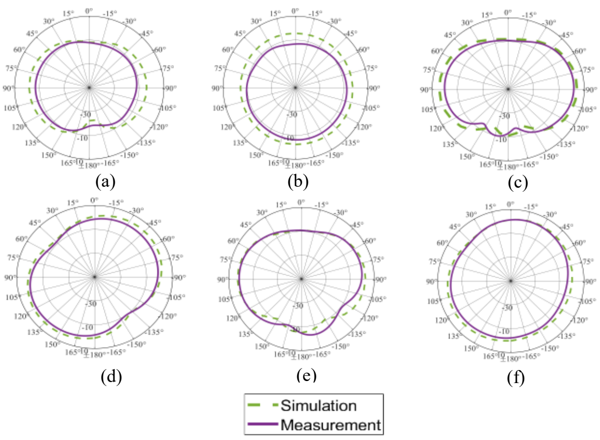


Fig. 6. Antenna radiation pattern (a) E-field (900MHz); (b) H-field (900MHz); (c) E-field (1800MHz); (d) H-field (1800MHz); (e) E-field (2100MHz); (f) H-field (2100MHz).

TABLE I. GAIN OF THE ANTENNA

Frequency (MHz)	Gain (dB)	
	Simulation	Measurement
900	0.5	-0.8
1800	5.4	4.7
2100	3.4	2.3

V. CONCLUSION

This paper presents fully printed triple-band 3D cube-shaped Cantor fractal antenna for RF energy harvesting applications. The advantages of this antenna are that it operates at three frequencies simultaneously (900MHz, 1800MHz, 2100MHz), it is low cost and compact in size. The triple-band performance is achieved through using Cantor fractal concept. Low cost and small size is a result of utilizing the concept of system-on-package. Additional cost-cutting is provided by use of additive manufacturing techniques like 3D printing and screen printing. Finally, the antenna shows decent performance in terms of gain and bandwidth. All the characteristics of the antenna make it good candidate for future RF energy harvesting applications of IoT.

ACKNOWLEDGMENT

Authors would like to acknowledge KAUST Sensor Initiative (OSR-2015-Sensors-2700) for financial support.

REFERENCES

[1] H. Sun, Y.-X. Guo, M. He, and Z. Zhong, “A dual-band rectenna using broadband Yagi antenna array for ambient RF power harvesting,” IEEE Antennas Wireless Propag. Lett., vol. 12, pp. 918–921, 2013

[2] J. O. McSpadden, Lu Fan and Kai Chang, "Design and experiments of a high-conversion-efficiency 5.8-GHz rectenna," in IEEE Transactions on Microwave Theory and Techniques, vol. 46, no. 12, pp. 2053-2060, Dec. 1998.

[3] J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic, “Recycling ambient microwave energy with broad-band rectenna arrays,” IEEE Trans. Microw. Theory Techn., vol. 52, no. 3, pp. 1014–1024, Mar. 2004.

[4] V. Kuhn et al., “A multi-band stacked RF energy harvester with RF-to DC efficiency up to 84%,” IEEE Trans. Microw. Theory Techn., vol. 63, no. 5, pp. 1768–1778, May 2015.

[5] V. Palazzi et al., "A Novel Ultra-Lightweight Multiband Rectenna on Paper for RF Energy Harvesting in the Next Generation LTE Bands," in IEEE Transactions on Microwave Theory and Techniques, vol. PP, no. 99, pp. 1-14.

[6] M. Piñuela, P. D. Mitcheson and S. Lucyszyn, "Ambient RF Energy Harvesting in Urban and Semi-Urban Environments," in IEEE Transactions on Microwave Theory and Techniques, vol. 61, no. 7, pp. 2715-2726, July 2013.

[7] A. Bakytbekov, T. Nguyen, C. Huynh, K. Salama, A. Shamim, “Fully Printed 3D Cube Multiband Fractal Rectenna for Ambient RF Energy Harvesting”, in Nano Energy, 2018.

[8] B. B. Mandelbrot, The Fractal Geometry of Nature: W. H. Freeman, New York, NY, USA, 1983.

[9] A. Bakytbekov, A. R. Maza, M. Nafe and A. Shamim, "Fully inkjet printed wide band cantor fractal antenna for RF energy harvesting application," 2017 11th European Conference on Antennas and Propagation (EUCAP), Paris, 2017, pp. 489-491.