Ultrathin Metamaterial-Inspired Huygens Dipole Antenna and Rectenna Arrays for Wireless Power Transfer Enabled IoT Applications

Wei Lin and Richard W. Ziolkowski
Global Big Data Technologies Centre,
School of Electrical and Data Engineering,
University of Technology Sydney,
Ultimo 2007, Sydney, Australia,
Email: Wei.Lin@uts.edu.au, Richard.Ziolkowski@uts.edu.au

***Abstract*-Ultrathin metamaterial-inspired Huygens dipole antenna and rectenna arrays are presented for wireless power transfer (WPT) enabled IoT applications. The fundamental array element is the electrically small Huygens dipole antenna (HDA) that consists of two metamaterial-inspired structures: an Egyptian axe dipole (EAD) and a capacitively loaded loop (CLL). The EAD and CLL are designed on both sides of a single PCB substrate functioning as the in-phase and orthogonal electric and magnetic dipoles. A short-driven dipole close to the CLL excites the two radiators. Based on the single element HDA, an ultrathin, beam-steerable Huygens dipole antenna array (HDAA) with wide area coverage and small gain variation has been developed as a long distance WPT transmitter for battery-free applications. Experimental verifications of the simulated results are presented. Additionally, an HDA-based Huygens dipole rectenna array (HDRA) design is developed for the receiver side. Effective capture of the wireless energy to power IoT devices is illustrated. Both DC and RF combining schemes are discussed for different application scenarios.**

***Index Terms*— Antenna arrays, beam-steering, electrically small antennas, Huygens dipole antennas, Internet-of-Things (IoT), wireless power transfer (WPT).**

I. Introduction

Wireless Internet-of-Things (IoT) applications have attracted more and more attention recently. They are expected to create immense economic growth in the near future [1]. Emerging IoT systems such as bushfire detection and warning sensor networks, digitalized agriculture, smart transportation and advanced manufacturing [2] will have huge societal impacts. Far-field wireless power transfer (WPT) is the enabling technology to realize battery-free IoT systems [3]. Wirelessly power systems will be lighter in weight and more environmentally friendly since they void the current need for bulky, short-life, non-degradable chemical batteries.

Transmitting antennas and receiving rectennas are two essential components in any far-field WPT system. The role of the transmitting antenna is to effectively deliver wireless power to remotely located IoT targets. As these targets, e.g., the IoT sensors, are normally widely distributed over a large area, the transmitting antenna is required to have high directivity for long distance transmission and broad beamwidth for large area coverage. Moreover, the entire design should be low cost and easy to fabricate. However, it is difficult to achieve all of these criteria simultaneously [4] – [6]. Receiving rectennas (rectifying antennas) must capture the incident wireless energy efficiently. In particular, rectennas are required to be compact, highly efficient, and easy and cost-effective to fabricate for IoT applications. It is also challenging to achieve all these features in a rectenna design at the same time [7] – [10].

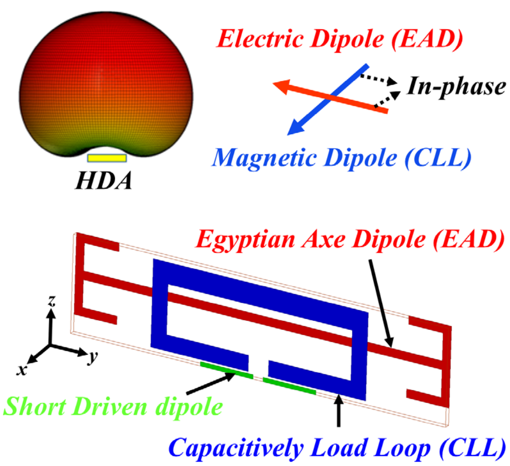


Figure 1. Ultrathin electrically small Huygens dipole antenna and its operating characteristics.

In this paper, we present the Huygens dipole antenna (HDA) and Huygens dipole antenna (HDAA) and rectenna (HDAA) arrays that we have developed with it to address these challenges. The fundamental element of these array designs is the ultrathin, electrically small HDA shown in Fig. 1. It is designed on a single piece of PCB substrate. It consists of two metamaterial-inspired electrically small structures: an Egyptian axe dipole (EAD) and a capacitively load loop (CLL), which form an orthogonal electric and magnetic dipole pair. The EAD and CLL are excited by a short driven dipole located on the same PCB side as the CLL. Being ultrathin and electrically small, the HDA radiates a cardioid-shaped Huygens pattern with a very broad beamwidth [11] – [13]. With these advantageous characteristics, the HDA is the ideal candidate as the element for the design of WPT transmitting and receiving arrays.

II. Huygens Dipole Antenna Array (HDAA) as a Wireless Power Transmitter

A. *Ultrathin, beam-steerable HDAA with wide area coverage and small gain variation*

Based on the single element HDA, an ultrathin, beam-steerable HDAA has been developed that achieves wide area coverage and small peak gain variation simultaneously. As seen in Fig. 2, the HDAs are placed in a linear uniformly-spaced array formation along the z-axis and are excited by sources with equal amplitude and variable phases. All of the HDA elements are designed and fabricated on the same single piece of the thin PCB substrate. This linear array retains the broad beamwidth of the HDA's pattern in the H-plane (*xoy*-plane), which is orthogonal to the plane of the array, and achieves a narrow beamwidth in the E-plane (*yoz*-plane), i.e., in that plane. Because the narrow beam can be steered into different directions, the HDAA achieves high directivity and wide area coverage at the same time.

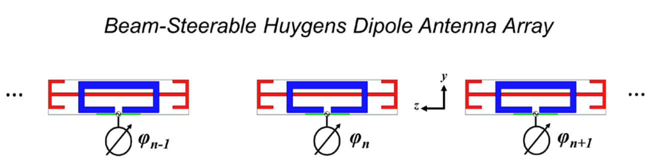
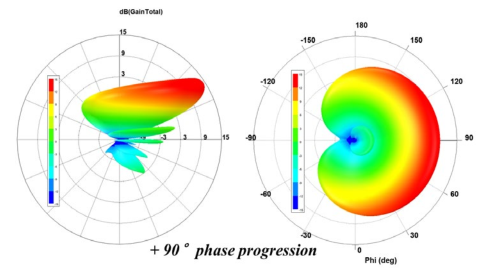


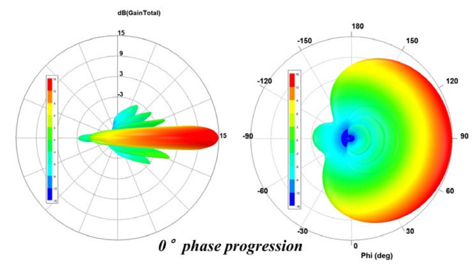
Figure 2. Configuration of the ultrathin, beam-steerable HDAA.

Another interesting feature of the HDAA is the small variation of the peak gain when the beam is steered into different directions. The comprehensive theoretical analysis of the beam-steerable HDAA in [14] has demonstrated that the peak gain variation is only 2.10 dB and 3.56 dB, respectively, for a 3-element and 9-element HDAA when their main beam is steered from broadside ($\theta = 90°$) to the direction parallel to the array axis ($\theta = 0°$ or 180°).

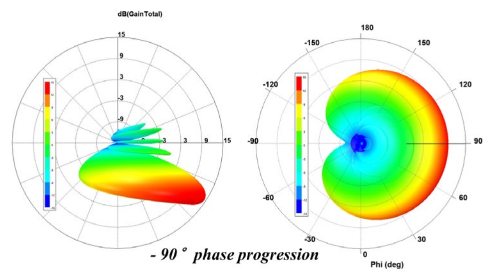
The full-wave radiation pattern simulations in ANSYS Electromagnetics Suite (HFSS), v. 18, of the 9-element HDAA in Fig. 3 confirm the theoretical analysis. The simulation model is designed to operate at 2.45 GHz. The array element center-to-center spacing is set at 0.45 λ_0. The 3D radiation patterns at 2.45 GHz are shown for equal amplitude excitations and with +90°, 0°, –90° phase progressions in the HDA elements. It is clearly observed that the peak gain variation is very small, less than 0.3 dB, when the main beam is steered ±33° relative to the broadside direction. Its H-plane patterns remain broad when the E-plane beam is steered. The 3-dB beamwidth of the broadside pattern covers 127° from −59° to +68°. The peak gain reaches 13.9 dBi and the front-to-back ratio (FTBR) value is 18.2 dB. These performance characteristics make the HDAA an ideal candidate to deliver wireless power from a WPT base station to a large number of remotely located IoT targets spread over a wide area at different elevation directions.



(a)



(b)



(c)

Figure 3. 3D radiation patterns demonstrate the beam-steerable, wide area coverage and small gain variation performance of the 9-element HDAA for different phase progressions in the excitations of its HDA elements. (a) +90°. (b) 0°. (a) -90°.

B. *Experimental verification*

To verify both the theoretical analysis and the full-wave simulations, a 3-element beam-steerable HDAA excited by a 3 × 3 Butler Matrix (BM) feed network has been developed. A photo of the prototype is presented in Fig. 4(a). The entire BM-fed HDAA was fabricated on a single piece of Rogers Duroid™ 5880 copper-clad substrate whose relative permittivity, loss tangent and thickness are 2.2, 0.0009 and 0.508 mm, respectively. The 3 × 3 BM consists of three 3-dB microstrip couplers. When any of the ports: Port#1 to Port#3, is excited, the three outputs, from the left to te right side, will have the same amplitude with a 0°, –120°, and +120° phase progression. To excite the three HDAs, three identical differential power divider transitions from a microstrip line to a co-planar twin line were employed.

Fig. 4(b) shows the measured $|S_{11}|$ and realized gain values as functions of the source frequency. The overlapped impedance bandwidth is 5.5%, covering 110 MHz from 2.395 to 2.505 GHz. The realized gain values are stable over the entire operating bandwidth. Noticeably, the gain variation is very small. The measured peak realized gain variation is only 0.5 dBi when the three ports were excited.

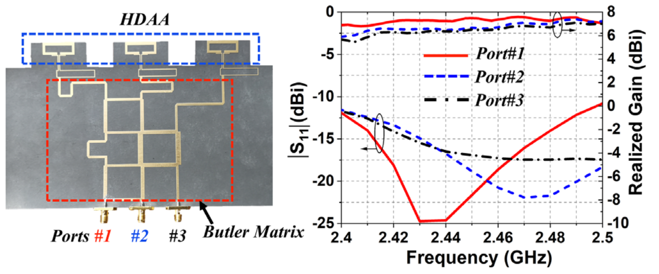


Figure 4. 3-element HDAA excited by a Butler Matrix. (a) Photo of the prototype. (b) Measured $|S_{11}|$ and realized gain values as functions of the source frequency for all three input ports.

Fig. 5(a) shows the normalized measured E-plane patterns for all three ports. Broad radiation coverage is confirmed. The E-plane patterns cover 121° from −63° to +58° with the measured gain variation less than 3.1 dB. Fig. 5(b) shows the normalized measured H-plane pattern for Port#1. A very wide beamwidth, covering 170° from −86° to +84°, was observed. The FTBR value is 18 dB.

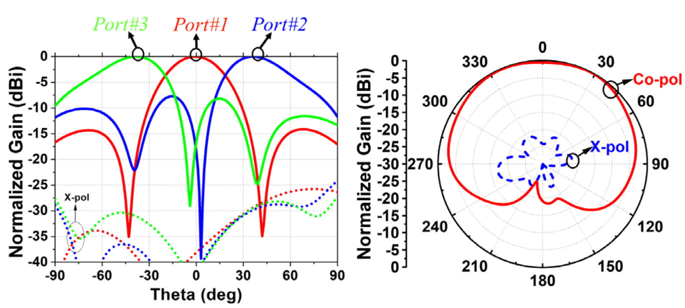


Figure 5. 3-element HDAA excited by a Butler Matrix. (a) Measured E-plane pattern for all three input ports. (b) Measured H-plane pattern for Port#1.

III. Huygens Dipole Rectenna Array (HDRA) as Wireless Power Receiver

Being compact and highly efficient, the HDA is an ideal candidate for the design of a rectenna array that captures transmitted wireless energy to power up IoT devices [15]. Single HDA-based rectenna designs have been developed in [16] – [18] and were demonstrated to have excellent AC-to-DC conversion efficiencies. To further enhance the wireless power capture capability of a system, rectenna arrays are required. Dependent on the scenario in which a wireless power density is established, rectenna arrays must adopt either a DC-combining or RF-combining topology.

A. HDRA with DC-combining

A HDRA with a DC-combining topology is illustrated in Fig. 6. Each HDA rectenna in the 4-element array works individually to capture the wireless power around it. The DC power output from each element is then combined together to attain the total DC power that can be delivered to a device. The 3D realized gain patterns of HDA#1 and HDA#2, the left two elements of the HDRA, are shown in Fig. 7. It is observed that the patterns radiated by both HDAs achieve good Huygens performance with broad beamwidths even in the presence of the other array elements. Due to the symmetry of the array, the patterns of HDA#3 and HDA#4 are symmetric to those of HDA#1 and HDA#2 and, thus, are not shown. The HDRA with a DC-combining scheme is suitable for electromagnetic (EM) wave environments in which the EM power density is evenly distributed, i.e, for situations in which the incident wireless power comes from any direction in the broadside hemisphere of the array.

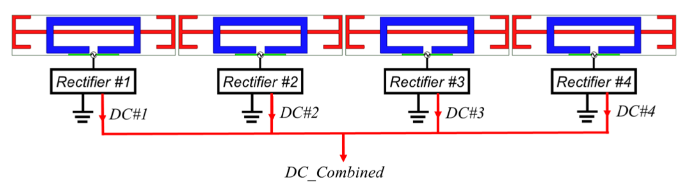


Figure 6. Four-element Huygens dipole rectenna array (HDRA) with a DC-combining topology.

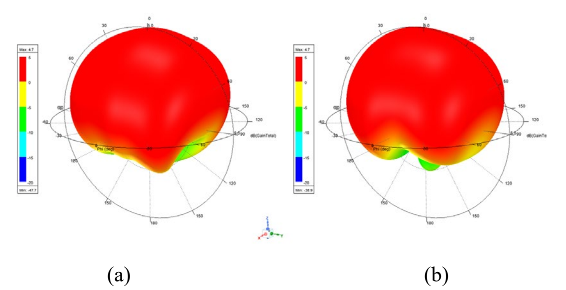


Figure 7. The 3D realized gain patterns of HDA#1 and HDA#2 as receiving elements in the four-element HDRA.

B. HDRA with RF combining

On the other hand, a HDRA with a RF-combining topology is suitable for point-to-point (P2P) WPT scenarios where the EM power density is mostly concentrated on a specific area. A four-element HDRA with a RF-combining topology is shown in Fig. 8. It would be most appropriate when the EM power from the transmitting antenna is delivered as a pencil beam. In such an application scenario, the EM power captured by each element of the HDAA is combined and then delivered to a single rectifier which yields a single DC output. Fig. 9 presents the 3D realized gain patterns of this four-element HDRA.

Notably, these patterns retain the narrow beam in the array plane and the wide beamwidth in the orthogonal plane attained with its transmitting antenna version.

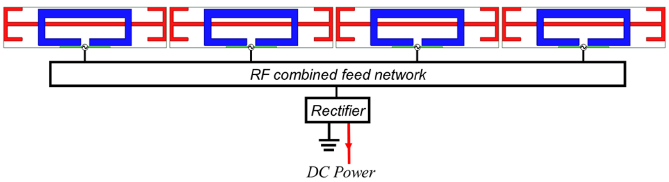
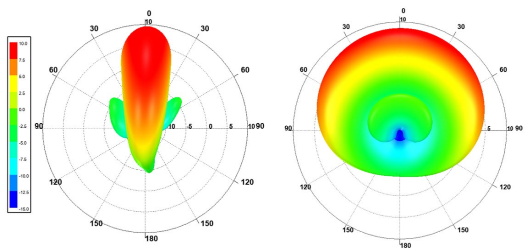


Figure 8. Four-element Huygens dipole rectenna array (HDRA) with a RF-combining topology.



(a) (b)

Figure 9. The 3D realized patterns of the 4-element HDRA. (a) E-plane. (b) H-plane.

IV. Conclusion

The ultrathin HDA element used in the design of transmitting and receiving arrays was first presented. Its Huygens cardioid performance was illustrated. The ultrathin beam-steerable transmitting HDAA formed with a set of these elements was shown to maintain the wide beamwidth of the individual element in the plane orthogonal to the array and to attain a narrow beamwidth in the plane of the array. Beam steering was demonstrated with only a small variation in the peak realized gain. The measured results of a 3-element BM-fed HDAA prototype were presented; they confirmed the simulated performance characteristics. The same HDA was then used to form ultrathin HDRAs in both DC-combining and RF-combining configurations. The presented transmitting and receiving HDAAs have attractive performance characteristics that can enable a wide variety of battery-free IoT applications as will be illustrated in our presentation.

References

[1] "Global IoT market & technology forecast to 2028", Market Info Group, Amsterdam, NH, Dec. 2019.

[2] A. Costanzo and D. Masotti, "Energizing 5G: Near- and far-field wireless energy and data transfer as an enabling technology for the 5G IoT," *IEEE Microw. Mag.*, vol. 18, no. 3, pp. 125-136, May 2017.

[3] N. B. Carvalho, et al., "Wireless power transmission: R&D activities within Europe," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 4, pp. 1031-1045, Apr. 2014.

[4] N. Ashraf, A.-R. Sebak, and A. A. Kishk, "PMC packaged single-substrate 4 × 4 Butler matrix and double-ridge gap waveguide horn antenna array for multibeam applications," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 1, pp. 248–261, Jan. 2021.

[5] Q. Wu, J. Hirokawa, J. Yin, C. Yu, H. Wang, and W. Hong, "Millimeter-wave multibeam endfire dual-circularly polarized antenna array for 5G wireless applications," *IEEE Trans. Antennas Propag.,* vol. 66, no. 9, pp. 4930–4935, Sep. 2018.

[6] K.-R. Xiang, F.-C. Chen, Q.-X. Chu, and M. J. Lancaster, "A broadband 3 × 4 Butler matrix and its application in multibeam antenna arrays," *IEEE Trans. Antennas Propag.,* vol. 67, no. 12, pp. 7622–7627, Dec. 2019.

[7] Z. Popovic, "Cut the cord: Low-power far-field wireless powering," *IEEE Microw. Mag.*, vol. 14, no. 2, pp. 55-62, Mar. 2013.

[8] V. Palazzi, et al., "A novel ultra-lightweight multiband rectenna on paper for RF energy harvesting in the next generation LTE bands," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 1, pp. 366-379, Jan. 2018.

[9] H. Sun, Y. X. Guo, M. He, and Z. Zhong, "Design of a high-efficiency 2.45-GHz rectenna for low-input-power energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 929–932, 2012.

[10] Z. Gu, S. Hemour, L. Guo, and K. Wu, "Integrated cooperative ambient power harvester collecting ubiquitous radio frequency and kinetic energy," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 9, pp. 4178-4190, Sep. 2018.

[11] R. W. Ziolkowski, "Low profile, broadside radiating, electrically small Huygens source antennas," *IEEE Access*, vol. 3, pp. 2644-2651, Dec. 2015.

[12] W. Lin and R. W. Ziolkowski, "Electrically-small, low-profile, Huygens circularly polarized antenna," *IEEE Trans. Antennas Propag*., vol. 66, no. 2, pp. 636–643, Feb. 2018.

[13] M. C. Tang, H. Wang and R. W. Ziolkowski, "Design and testing of simple, electrically small, low-profile, Huygens source antennas with broadside radiation performance," *IEEE Trans. Antennas Propag.*, vol. 64, no. 11, pp. 4607–4617, Nov. 2016.

[14] W. Lin and R. W. Ziolkowski, "Theoretical analysis of beam-steerable, broadside-radiating Huygens dipole antenna arrays and experimental verification of an ultrathin prototype for wirelessly powered IoT applications," *IEEE Open J. Antennas Propag.*, vol. 2, pp. 954–967, Sep. 2021.

[15] W. Lin and R. W. Ziolkowski, "Wirelessly powered temperature and light detecting sensors based on electrically small Huygens antennas," *Sensors*, vol. 19, No. 9, Apr. 2019.

[16] W. Lin, R. W. Ziolkowski and J. Huang, "Electrically small, low profile, highly efficient, Huygens dipole rectennas for wirelessly powering Internet-of-Things (IoT) devices," *IEEE Trans. Antennas Propag.*, vol. 67, No. 6, pp. 3670-3679, June 2019.

[17] W. Lin, and R. W. Ziolkowski, "Electrically small, single-substrate Huygens dipole rectenna for ultra-compact wireless power transfer applications," *IEEE Trans. Antennas Propag.*, vol. 69, No. 2, pp. 1130-1134, Feb. 2021.

[18] W. Lin and R. W. Ziolkowski, "Electrically small Huygens CP rectenna with a driven loop element maximizes its wireless power transfer efficiency," *IEEE Trans. Antennas Propag.*, vol. 68, No. 1, pp. 540-545, Jan. 2020.