mmWave Wireless Power Transmission to Flexible Rectennas in Absorptive and Reflective Media

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***Abstract*—Millimeter-Wave (mmWave) wireless power transmission (WPT) can provide theoretical improvements to the end-to-end link efficiency compared sub-6 GHz bands. However, mmWave propagation in the WPT is yet to be explored. Herein, we present the first evaluation of a broadband mmWave rectenna on a lossy phantom based on radiation absorbing material (RAM). The ground reflection is observed over distance from a 20 dBi horn antenna with a 1 W input around 23 and 28 GHz, where the effect of multi-paths reflections is demonstrated and compared to a varying input from the generator. A DC power output over 10 µis measured at 15 cm from a 51 dBm source, showing the potential for meters-range mmWave wearable WPT with the licensed 5G 75 dBm EIRP levels. It is concluded that the electromagnetic (EM) environment and propagation media can have significant influences on mmWave WPT requiring novel signal and EM co-design.**

I. Introduction

Millimeter-Wave (mmWave) bands have already been commercialized in cellular communication applications, with CMOS active components such as power amplifiers enabling a significantly reduced mmWave frontend cost [1]. mmWaves have been long considered for wireless power transmission (WPT) applications, particularly in space due to the absence of atmospheric attenuation [2], and more recently in low-power energy harvesting applications [3]. It was shown in non-linear [4] and earlier in linear [5] theoretical analysis that mmWave bands outperform their sub-6 GHz counterpart due to the higher EIRP and larger transmitting arrays.

A plethora of low-cost flexible and conformable mmWave rectennas have been reported including textile-based antennas [4], [6] and flexible harvesters [7]. In addition, arrays with integrated rectifiers have recently been investigated beyond 60 GHz [8]. Nevertheless, most rectennas were characterized in controlled environment with no consideration of their surroundings, whereas it is well-known that mmWaves suffer from additional absorption, diffraction, and shadowing, particularly near lossy media [9]. Thus, further experimental work is needed to consider the holistic effects of the propagation medium and the rectenna's non-linearity, to further evaluate the feasibility of mmWave WPT.

In this paper, we present an experimental evaluation of a flexible wearable mmWave rectenna on a lossy surface and in close proximity with a partially reflective surface. The ground reflection effects are demonstrated on the DC output along with the rectenna's ability to generate over 0.1 mW DC output from a 29 GHz input at 10 cm from a 50 dBm source.

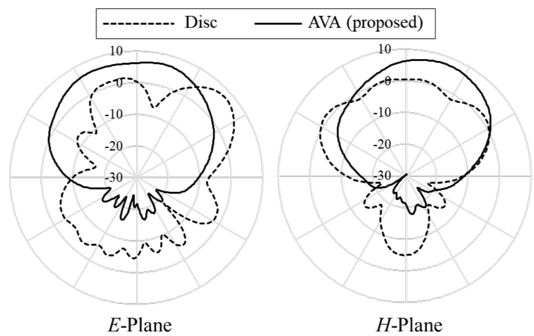

Fig. 1. Simulated far-field gain of the PEC-backed AVA [6] compared to a PEC-backed disc [10].

II. Reflector-Back Rectenna

To deploy mmWave rectennas on lossy media such as the human body, a decoupling mechanism is required. Microstrip patch antennas typically suffer from a reduced radiation efficiency on thin substrates, and from a relatively narro bandwidth [4], [6]. Thus, the investigated design, implemented on a textile substrate, is based on a broadband Vivaldi-inspired design backed by a conductive textile plane to minimize interaction with the human body and achieves a minimum radiation efficiency of 67% [6].

However, PEC-backing does not always lead to a uniform broadside pattern, and the original structure needs to be directive. Fig. 1 compares the simulated radiation patterns of the reflector-backed antipodal vivaldi antenna (AVA) with a simple broadband disc monopole [10], where it can be seen that the AVA-inspired design provides a more uniform broadside beam, lower side-lobes, and a higher peak gain.

III. Experimental Results and Discussion

A. mmWave WPT Setup

A Mini-Circuits ZVE-453HP+ 18-45 GHz power amplifier (PA) was connected to a Wiltron signal generator to generate an approximately 1 W mmWave input to the transmitting antenna. A WR-34 (22-33 GHz) horn with a nominal gain of 20 dBi was connected to the PA through an isolator with under 1 dB insertion loss. The rectifier operates efficiently for inputs between 0 and 10 dBm, with a 1 V DC output across a 5 kΩ load up between 20 and 26.5 GHz for a 10 dBm input, based on [6]. Fig. 2(a) and (b) shows the experimental setup's block diagram and photograph, respectively.

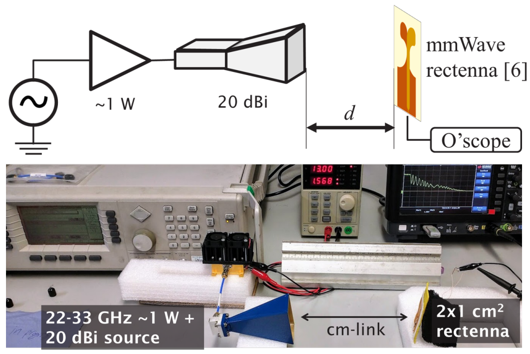

Fig. 2. Experimental setup of the mmWave rectenna on a lossy and reflective medium: (a) block diagram; (b) photograph.

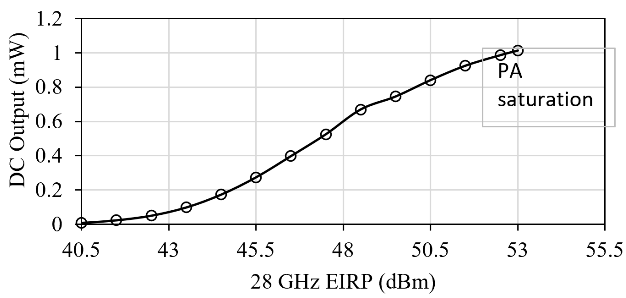

Fig. 3. Measured DC output of the rectenna at 3 cm from the horn's aperture at 28 GHz for varying inputs from the generator.

B. Distance and Radiated Power Sweep

To observe the non-linear response of the rectenna, the power input from the signal generator was varied from −15 to 0 dBm. With an approximate loss of 4.5 dB from the isolator, the cabling, and the interconnects, the PA is driven close to its saturated output of 32 dBm which limits the equivalent isotropic radiated power (EIRP) to 52 dBm. Fig. 3 shows the DC output of the rectenna t 3 cm from the horn's aperture which matches the typical rectifier's non-linear RF-DC efficiency response.

To compare the ideal incident plane wave variation to realistic propagation environments, the setup shown in Fig. 2(b) was used with the rectenna mounted on a radiation absorbing material (RAM) block. The distance was varied for two inputs, at 23.3 and 28.3 GHz, to observe the multi-path reflections, predominantly from the wooden surface of the work emulating the ground reflection losses. Fig. 4 shows the measured DC output of the rectenna as a function of distance.

The observed fluctuations match the ground reflection loss, which demonstrates the need for multi-band mmWave WPT, as well as signal processing mechanisms for controlling the multi-path effects. Furthermore, it can be seen that with the 31 dBm source and 20 dBi horn, over 10 μW could be received at 15 cm by a highly miniaturized (2 cm^2) and low-profile (<1 mm-thick) rectenna. Should a 72 EIRP dBm be used, the 20 dB increase in the transmitted power could enable a transmission range in excess of 1 m to ultra-compact wearable rectennas on lossy materials.

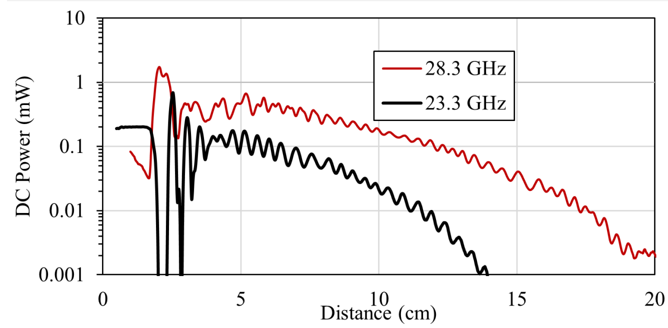

Fig. 4. Rectenna's DC output over distance for a fixed EIRP ≈ 51 dBi.

IV. Conclusions

We presented an experimental evaluation of mmWave WPT in a practical EM environment. It is shown that ground reflections must be considered and the EM propagation environment needs to be engineered for efficient mmWave WPT. With over 10 μW rectified DC power from the 2 cm^2 rectenna, mmWave WPT is a strong candidate for ultra-compact WPT.

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References

[1] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5g cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.

[2] T.-W. Yoo and K. Chang, "Theoretical and experimental development of 10 and 35 GHz rectennas," *IEEE Trans. Mirow Theory Techn.*, vol. 40, 6, pp. 1259 – 1266, 1992.

[3] M. Wagih, A. S. Weddell, and S. Beeby, "Millimeter-Wave Power Harvesting: A Review," *IEEE Open Journal of Antennas and Propagation*, vol. 1, pp. 560 – 578, 2020.

[4] M. Wagih, G. S. Hilton, A. S. Weddell, and S. Beeby, "Millimeter Wave Power Transmission for Compact and Large-Area Wearable IoT Devices based on a Higher-Order Mode Wearable Antenna," *IEEE Internet of Things Journal*, pp. 1–1, 2021.

[5] T. A. Khan, A. Alkhateeb, and R. W. Heath, "Millimeter Wave Energy Harvesting," *IEEE Trans. Wireless Communications*, vol. 15, 9, pp. 6048 – 6062, 2016.

[6] M. Wagih, G. S. Hilton, A. S. Weddell, and S. Beeby, "Broadband Millimetre-Wave Textile-based Flexible Rectenna for Wearable Energy Harvesting ," *IEEE Trans. Microw Theory Techn*, vol. 68 no. 11, pp. 4960 – 4972, 2020.

[7] C. Song, Y. Ding, A. Eid, J. G. D. Hester, X. He, R. Bahr, A. Georgiadis, G. Goussetis, and M. M. Tentzeris, "Advances in wirelessly powered backscatter communications: From antenna/rf circuitry design to printed flexible electronics," *Proceedings of the IEEE*, vol. 110, no. 1, pp. 171–192, 2022.

[8] Y. Wang, X.-X. Yang, G.-N. Tan, and S. Gao, "Study on Millimeter-Wave SIW Rectenna and Arrays with High Conversion Efficiency," *IEEE Transactions on Antennas and Propagation*, pp. 1–1, 2021.

[9] N. Chahat, M. Zhadobov, L. L. Coq, S. I. Alekseev, and R. Sauleau, "Characterization of the Interactions Between a 60-GHz Antenna and the Human Body in an Off-Body Scenario," *IEEE Trans. Antennas Propag.*, vol. 60, 12, pp. 5958 – 5965, 2012.

[10] J. Liang, C. Chiau, X. Chen, and C. Parini, "Study of a printed circular disc monopole antenna for uwb systems," *IEEE Trans. Antennas Propag.*, vol. 53, no. 11, pp. 3500 – 3504, 2005.