Extending the Range of 5G Energy Transfer: Towards the Wireless Power Grid

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Abstract— **In this work, the authors demonstrate the potential of 5G/mm-wave signals, coupled with wide-coverage Rotman-lens-based harvesters (a.k.a. tag) to achieve efficient and long-range powering. First, the rationale for the approach is described, before the elements of the harvester and their design specifications are presented and their performance is reported. Finally, the emitting system is detailed, followed by the presentation of its use with the tag to demonstrate long-range wireless power transfer (WPT) at mm-wave frequencies. For the first time, a relatively-compact rectenna system is shown to be able to collect 5G signals at ranges exceeding $16\,\mathrm{m}$ with a wide angular coverage, thereby extending the range relative to previous efforts by more than 5x and demonstrating a pathway towards the emergence of the Wireless Power Grid (WPG), a key to enabling the accelerated deployment of energy-autonomous wireless sensors ubiquitous constellations for digital twinning, smart cities, and intelligent infrastructure.**

Keywords— **5G, energy harvesting, wireless power transfer, IoT, millimeter-waves, rectenna, rectifying circuit.**

I. Introduction

The scientific and engineering literature in the field of wireless power transfer (WPT) is densely populated with examples of systems employing (even at rather long ranges [1]) frequencies lower than $2.5\,\mathrm{GHz}$, with the most common work occurring at low MHz frequencies and with the use of tightly-coupled non-radiating coil couples. Nevertheless, a cursory consideration of the fundamental properties of electromagnetic radiators and of the spherical waves that they generate leads to the conclusion that only emitters capable of tightly focalising the electromagnetic energy that they radiate—and, therefore, displaying high antenna gains—could ever lead to efficient wireless energy transfer. Over the dimensions that most commercial antenna systems occupy, the achievement of appropriately high gains requires the use of mm-wave frequencies. It was recently identified that a system featuring hardware with such capabilities had been approved by regulators, was being massively deployed, and could, therefore, be employed for the purpose of powering devices wirelessly: 5G [2]. Nevertheless, the same physical properties—electrically large apertures—allowing the focalization of the emitted power comes back to bite the designer of the receiving end of the system. Indeed, receivers with apertures large enough to receive significant enough amounts of power quickly become anisotropic in their performance: their orientation vis-à-vis the emitter cannot be random. Fortunately, recent research has shown how this problem can be circumvented using a receiving structure enabled by an unlikely component: the Rotman lens [2], [3].

In this work, we present the longest range ever-reported 5G/mm-wave powering using a Rotman lens-based rectenna. Building on a structure previously reported in [3], [2], the system was re-designed, simulated and fabricated on a different substrate with a new rectifier design. The long-range harvesting capabilities were tested using a high performance transmitting antenna system providing a total EIRP of around $65\,\mathrm{dBm}$. The paper highlights the basic elements of the rectenna system and discusses the effect of the DC block capacitor on the power conversion efficiency of the rectifier, before diving into the experimental wireless setup evaluating the maximum powering range.

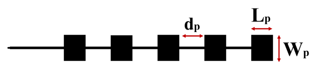
II. MM-Wave Rectenna Elements

A. Series-Fed Patch Antenna Array Design

Patch antennas are a very common choice in the design of mm-wave antenna arrays due to their simplicity, full-ground plane—desirable for most applications—,good gain and broad beamwidth. In this work, arrays consisting of five serially-fed patch antennas with dimensions shown in Fig. 1a were designed, simulated and fabricated on copper-clad Rogers RO4350B substrate ($\varepsilon r = 3.66$ and h = $168\,\mu\mathrm{m}$). Five elements per array form an E-plane beamwidth of about 18°, found compatible with most planar environments. Fig. 1b shows the simulated and measured S_{11} results of the 5-element array, displaying an operation at $27.5\,\mathrm{GHz}$ with a reflection coefficient lower than $-20\,\mathrm{dB}$ within this range. While the antenna was designed to operate at $28\,\mathrm{GHz}$ as observed in the simulated plot, manufacturing tolerances influenced the resonance frequency and resulted in the observed detuning. The antenna array formed with five antennas displays a vertical beamwidth of about 20° that is found convenient for most use cases, where environments expand mostly horizontally. Its simulated gain is $13\,\mathrm{dBi}$ and horizontal beamwidth is $80°$.

B. $28\,\mathrm{GHz}$ *Rectifier Design*

The design of efficient and sensitive rectifiers at mm-wave frequencies is challenging with the commercially-available easily-mountable Schottky diodes due to their high packaging parasitics. Lower turn-on power densities or higher power conversion efficiencies can be realized with CMOS technologies and diodes in die forms [4], [5]. In this work, and due to ease of integration, we use the MA4E1317 GaAs Schottky diode from Macom, that has a high cut-off frequency and low capacitance and series resistance, compatible with the operation at mm-waves. The schematic presented in Fig. 2a shows the design of the mm-wave rectifier simulated and fabricated in this work. The rectifier, fabricated on the same substrate used for the antennas, consists of a single Schottky diode connected in series, preceded by a matching network and followed by harmonic terminations. Since the antenna and rectifier elements are all RF combined through the Rotman lens as will be shown in the next section, the incorporation of an SMD capacitor



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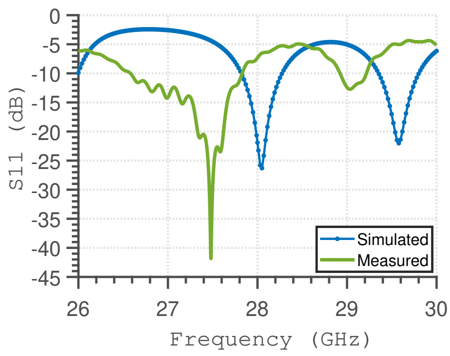

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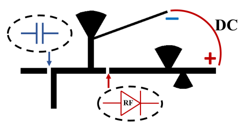
Fig. 1. (a) Schematic of the series-fed patch antenna array with $Wp = 3.6mm$, $Lp = 2.74mm$ and $dp = 2.8mm$, (b) Plots of the simulated and measured S_{11} of the antenna array.



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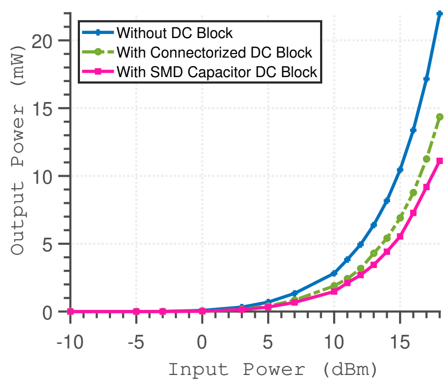

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Fig. 2. (a) Schematic of the mm-wave rectifier with length $L = 12mm$ and width $W = 8mm$, (b) Plots of the measured output powers vs input power of the rectifier with and without a DC Block for a load of 980 Ω.

DC block before the diode was necessary to ensure that the rectifier elements are not connected in DC at their inputs. However, as shown in Fig. 2b, achieving this functionality comes at the cost of the efficiency of the rectifier. The plots show the output powers of two different rectifiers measured at 28 GHz using a load of 980 Ω: a rectifier designed without a DC block and tested with and without a connectorized DC block, while the second rectifier is designed with an SMD capacitor DC block. The results show that both DC blocks (connectorized and SMD) cause an insertion loss of around 2 dB, resulting in a major decrease in the DC output power by almost 50%. While the capacitor-less rectifier realizes an efficiency of 35% at 18 dBm, the other reaches a peak of 20% for the same input power. The comparison between the connectorized DC block and SMD capacitor was necessary to validate the proper operation of the chosen capacitor as a DC block with minimal influence on the mm-wave signal. Based on the three tests measured similarly at 28 GHz, the capacitor's behavior is very comparable to that of a connectorized DC block operating up to 40 GHz. While it is challenging to find capacitors with mm-wave cut-off frequencies, this capacitor, despite causing a decrease in the efficiency, removes the necessity of parallelizing the outputs of all six rectifiers connected through the lens, as presented in the following section.

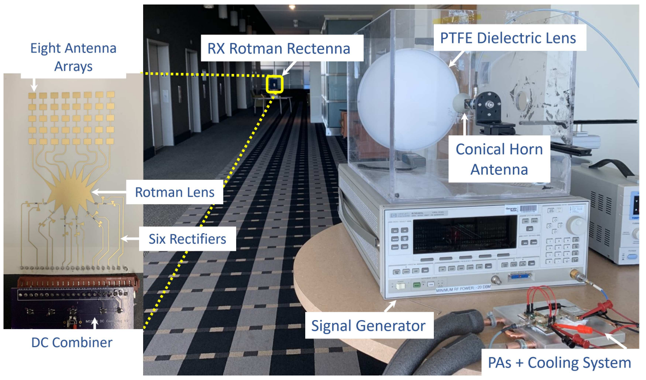
III. Long Range MM-Wave Powering

A. *mm-wave Rotman Lens Rectenna*

The design of the rectenna was then completed with the addition of the Rotman lens presented previously in [3], [2] between the antennas and the rectifiers, however designed for this work on RO4350B. The Rotman lens has been demonstrated to be the key element to the realization of simultaneous high gain and orientation agnostic harvesting. Our previous fully-printed and planar Rotman antenna array fabricated on Liquid crystal polymer (LCP) substrate ($\varepsilon r = 3.02$ and h = 180 µm) displayed a measured gain of approximately 17 dBi, and an angular coverage of around 110°. The resulting Rotman rectenna demonstrated 6 dB lower turn-on sensitivity compared to a non-Rotman rectenna of the same size and 21-fold increase in harvested power for the same angular coverage. However, in previous works, the long-range capabilities of the Rotman lens rectenna were not fully-tested due to the inability (at the time) to send more than 54 dBm EIRP. In this work, all elements (antennas, rectifiers and Rotman lens) were redesigned on a new substrate, and combined together to realize the structure shown in Fig. 3a. As described in more details in [2], the Rotman lens is a scalable, ultra-broadband structure. The choice of the number of the antenna and beam ports surrounding it was determined based on a scalability study analyzing the effect of the Rotman lens' size on its array factor and angular coverage. The study concluded that eight antenna ports and six beam ports offer a good combination of the aforementioned parameters. As shown in Fig. 3a, eight serially-fed patch antenna arrays were connected to the lens from one side, while six rectifiers were connected at the beam ports on the opposite side. It can be clearly seen now why the addition of SMD capacitors as DC blocks at the input of the rectifiers was crucial. Since the implementation of the Rotman lens enables the RF combination and focalization of all the signals collected by the antennas to one beam port where the rectifier is located, it was necessary to design a unique DC combiner based on bypass diodes to allow the collection of the DC power irrespective of the angle of the incident signal.

B. *Testing the rectenna at long range*

The long range capabilities of the Rotman lens rectenna were evaluated in an indoor environment as shown in Fig. 3a. The harvester was placed at different distances away from the transmitter and rotated at different angles to simultaneously asses its orientation agnostic abilities. Fig. 4 describes in more details the setup used to enable the



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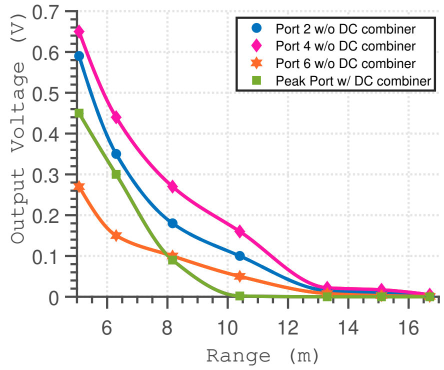

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Fig. 3. (a) Picture of the setup used to measure the long range capabilities of the Rotman harvester, (b) Plots of the measured output voltages of the Rotman rectenna vs range at different ports without the DC combiner and at the peak port with the DC combiner.

transmission of around 65 dBm EIRP. A signal generator provided a continuous wave signal at 27.5 GHz to two cascaded power amplifiers—the AHP2850-18-3024 from Wenteq Microwave Corp and the QPA2212 from Qorvo—capable of outputting 40 dBm of power, followed by a in-house design of a high gain antenna system composed of a 19 dBi conical horn antenna and a high directivity 300 mm-diameter PTFE dielectric lens providing an additional 10 dB of gain. The resulting transmitted EIRP was calculated to be around 65 dBm taking into consideration the losses in the cables, connectors and lens focal points adjustments. The range test was repeated with and without the DC combiner to highlight its effect on the collected DC power. While the DC combiner is crucial for the operation of this system in an orientation agnostic manner, it degrades the incident power density sensitivity by 4 dB under open load conditions, as presented in more detail in [2]. The degradation is induced by the use of bypass diodes that pull the rectified voltage down by 0.1 V to 0.2 V. Therefore, the preliminary proof-of-concept test was conducted without a DC combiner, and evaluated the output voltage of the rectenna at three different ports corresponding to three different incidence angles: port 2 corresponds to an incidence angle at −30°, port 4 at 10°, and port 6 at 45°. Fig. 3b shows the ability of the system to achieve up to 16.7 m of powering range without a DC combiner, i.e. with prior knowledge of source's incidence angle, and up to 10.4 m of powering range while being orientation agnostic, demonstrating (to our knowledge) the

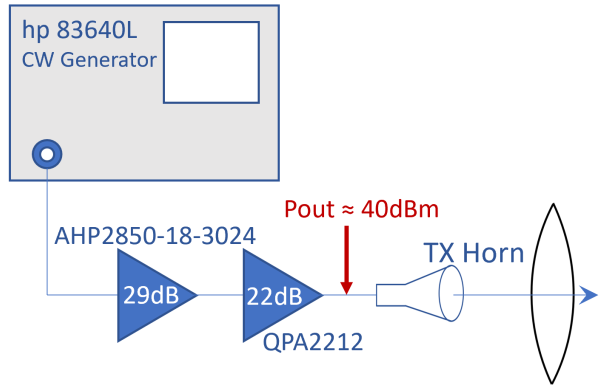

Fig. 4. Schematic describing the high performance transmitter setup.

longest mm-wave powering range ever reported in the academic literature and is already adequate for the powering of mmID tags [6] and ubiquitous sensing devices at ranges in excess of 10 m away from the emitter.

IV. Conclusions

This paper demonstrated an efficient and, more importantly, very scalable method for the design of highly-sensitive and orientation-agnostic mm-wave harvesters. The reported emitter system stills falls 10 dB short of the 75 dBm EIRP regulatory limit for 5G base-stations, thereby leaving behind a 3x to 4x increase (taking into account the detuning of the reported receiver's antenna) in range potential. Furthermore, the employment of rectifiers in Complementary Metal–Oxide–Semiconductor (CMOS) technology [7], [8], [9] instead of commercial off-the-shelf Schottky diodes—which fall short at mm-wave frequencies starting at 24 GHz [10], [4] due to their high parasitic losses—presents a pathway towards the emergence of receivers capable of being powered from the very edges of the 5G cells, 180 m away from the base station. Coupled with the ultra-low power and long-range backscattering communications architectures empowered by 5G [11], [6], mm-wave fully-passive RFID systems are emerging, enabling the accelerated deployment of energy-autonomous wireless sensors for digital twinning, and smart cities and infrastructures.

References

[1] N. Shinohara, "Power without wires," *IEEE Microwave magazine*, vol. 12, no. 7, pp. S64–S73, 2011.

[2] A. Eid, J. G. Hester, and M. M. Tentzeris, "5g as a wireless power grid," *Scientific Reports*, vol. 11, no. 1, pp. 1–9, 2021.

[3] A. Eid, J. Hester, and M. M. Tentzeris, "A scalable high-gain and large-beamwidth mm-wave harvesting approach for 5g-powered iot," in *2019 IEEE MTT-S International Microwave Symposium (IMS)*, June 2019, pp. 1309–1312.

[4] M. Wagih, A. S. Weddell, and S. Beeby, "Millimeter-wave power harvesting: A review," *IEEE Open Journal of Antennas and Propagation*, 2020.

[5] A. Eid, J. Hester, B. Tehrani, and M. Tentzeris, "Flexible w-band rectifiers for 5g-powered iot autonomous modules," in *2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, 2019, pp. 1163–1164.

[6] A. Eid, J. G. Hester, and M. M. Tentzeris, "Rotman lens-based wide angular coverage and high-gain semipassive architecture for ultralong range mm-wave rfids," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 11, pp. 1943–1947, 2020.

[7] M. Nariman, F. Shirinfar, S. Pamarti, A. Rofougaran, and F. De Flaviis, "High-efficiency millimeter-wave energy-harvesting systems with milliwatt-level output power," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 64, no. 6, pp. 605–609, 2016.

[8] N. Weissman, S. Jameson, and E. Socher, "W-band cmos on-chip energy harvester and rectenna," in *2014 IEEE MTT-S international microwave symposium (IMS2014)*. IEEE, 2014, pp. 1–3.

[9] H. Gao, D. M. Leenaerts, and P. Baltus, "A 58-64 ghz transformer-based differential rectifier in 40 nm cmos with-12 dbm sensitivity for 1 v at 64 ghz," in *2019 IEEE MTT-S International Microwave Symposium (IMS)*, 2019, pp. 1306–1308.

[10] C. R. Valenta and G. D. Durgin, "Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems," *IEEE Microwave Magazine*, vol. 15, no. 4, pp. 108–120, 2014.

[11] J. G. Hester and M. M. Tentzeris, "A mm-wave ultra-long-range energy-autonomous printed rfid-enabled van-atta wireless sensor: At the crossroads of 5g and iot," in *Microwave Symposium (IMS), 2017 IEEE MTT-S International*. IEEE, 2017, pp. 1557–1560.