DC Power Pattern Analysis of N-by-N Staggered Pattern Charge Collector and N^2 Rectenna Array

Blake R. Marshall, Christopher R. Valenta, and Gregory D. Durgin
School of Electrical and Computer Engineering
Georgia Institute of Technology Atlanta, Georgia 30332 USA
bmarshall9@gatech.edu, christopher.valenta@gatech.edu, durgin@ece.gatech.edu

***Abstract*—This paper compares a 4-by-4 dipole staggered pattern charge collector (SPCC) rectenna array to a 16 dipole rectenna array arranged in a four series-four parallel configuration. While each of these energy harvesting circuits has an identical footprint, the SPCC has a DC power pattern which simultaneously provides high gain and wide beamwidth. This profile provides RF energy harvesting sensors with additional range and makes them less sensitivity to orientation. At 0.1 m range, the N^2 rectenna has a peak DC voltage 20% larger than the SPCC, but the SPCC's beamwidth is 400% larger than the N^2 rectenna array. At 1 m range, the SPCC beamwidth is 600% larger, and the peak voltage is 300% larger than the N^2 rectenna control case.**

I. Introduction

Radio frequency energy harvesting has become an important research area for low power/passive sensors in wireless sensor networks (WSNs) as well as for wireless power transmission systems. Each of these applications has unique requirements which drastically changes the energy harvesting system design. Wireless power transmission systems typically deal with large amounts of power, and energy conversion efficiency is of paramount importance. Therefore, adaptive arrays and high gain antennas can be used to obtain the highest incident power (and therefore efficiency) onto the harvesting circuit [1] [2]. Conversely, WSNs are more cost and size constrained, so complicated adaptive beam forming networks are not practical. Furthermore, sensor mote positions are unknown a-priori, so high gain, narrow beamwidth antennas are not useful.

Staggered pattern charge collectors (SPCCs) are a configuration of antennas and energy harvesting circuits that increases RF energy harvesting efficiency by using aimed sub-arrays with high gains. The effective DC power pattern [3] maintains a more constant output power across angles than a single rectenna array. In effect, a high aggregate gain antenna pattern is realized without limiting the beamwidth [4]. This functionality is especially beneficial to RF energy harvesting sensors whose position is often uncontrollable.

The remainder of this paper is organized as follows: section II discusses the SPCC design and simulation, section III outlines the energy harvesting circuitry effect on the SPCC and specifically discusses the designed single shunt rectenna utilized for these simulations, section IV discusses the simulations of the N^2 rectenna array and the 4-by-4 SPCC, section V analyzes the results of these simulations, and section VI concludes this paper.

II. Staggered Pattern Charge Collector

A. Theory

SPCCs are a group of N sub-arrays that harvest RF energy fed to a common capacitor as shown in Fig. 1. The received power for each sub-array is passed into an energy harvester which are combined in parallel or series across a common load depending on the specific implementation.

The multiple sub-arrays are pointed in different directions to create an aggregate gain pattern [4] [5]. The aggregate gain pattern approximates the SPCC pattern well by taking the maximum of all sub-array patterns, but does not include each sub-array harvesting when there are low incident power levels. To improve on the aggregate gain pattern (AG) for energy harvesting, the *summation gain* is defined as the summation of each sub-arrays's gains G_n as shown in (1). The summation gain (SG) has a similar shape to the aggregate gain pattern but includes information about sub-array beam overlaps, which better predicts the DC power pattern on the output.

$$SG = G_1 + G_2 + \ldots + G_N \quad (1)$$

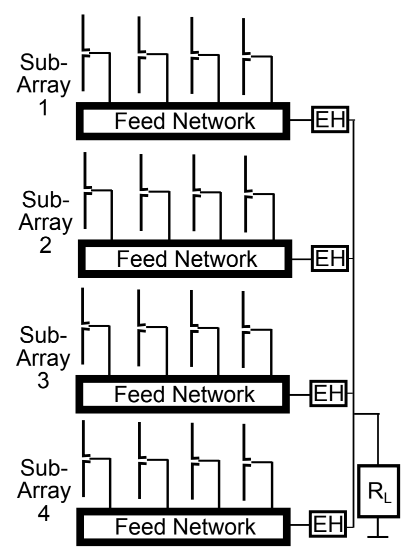

Fig. 1. Schematic drawing of implemented 4-by-4 SPCC showing the sub-arrays and energy harvesting connections.

B. 4-by-4 Staggered Pattern Sub-Arrays

The SPCC, shown in Fig. 1 can use any value of N to create an aggregate gain pattern for comparison, but, in this paper, a 4-by-4 SPCC of dipoles is used and compared to a 16 dipole rectenna array. The theory for designing a SPCC is outlined in [5]. The antenna phase offsets β_{nm} used for this 4-by-4 SPCC are summarized in Table I.

Each antenna in each sub-array has a different phase offset to direct the main beams in different directions to widen the coverage. The bottom two sub-arrays have negative phases of the top two which means the final aggregate gain and summation gain patterns must have symmetry. Using CST, the sub-arrays were built from dipoles and phase offsets.

TABLE I
SPCC SUB-ARRAY ANTENNA PHASE OFFSETS (DEGREES)

SPCC	ANT 1	ANT 2	ANT 3	ANT 4
Sub-array 1	0	170	110	280
Sub-array 2	0	130	20	150
Sub-array 3	0	-130	-20	-150
Sub-array 4	0	-170	-110	-280

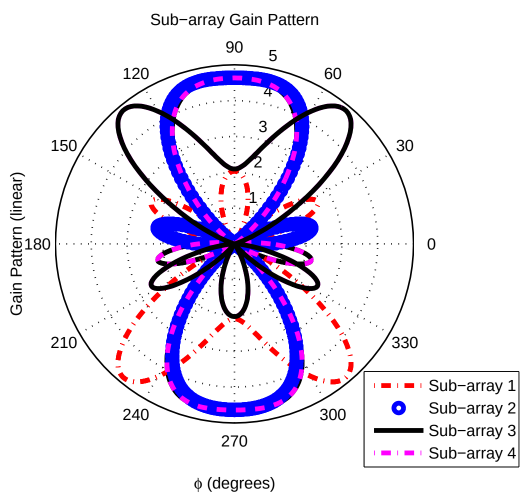

Fig. 2. Each sub-array gain pattern for the SPCC shown in linear units. The sub-arrays are pointed in different directions to produce larger coverage than a single array, and the realized gains are higher than a single antenna.

The four resulting gain patterns for each sub-array are shown in Fig. 2. The realized gain for each sub-array peaks at 7 dB with the main beams in different directions to create coverage. Sub-array 2 and sub-array 4 have similar patterns to ensure a high summation gain over the middle of coverage.

III. ENERGY HARVESTING CIRCUITRY

Although any type of energy harvesting circuit topology could be used with a SPCC, a single shunt rectenna was chosen as it is typically the most efficient design due to using only a single diode. Its schematic is shown in Fig. 3. Avago HSMS-2862 diodes are used in the SOT-143 package. These diodes were selected for their low turn-on voltage of 300 mV, and the

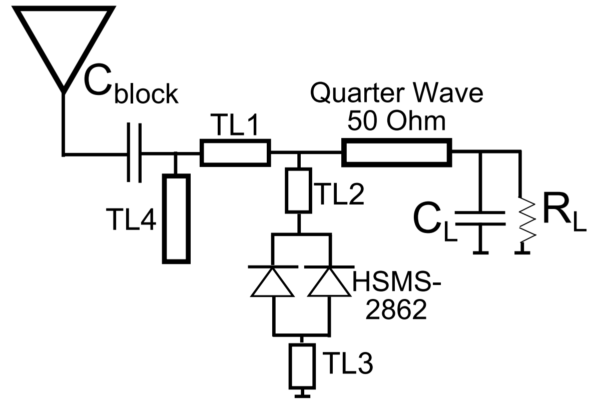

Fig. 3. Rectenna schematic showing the open circuited matching stub, $TL4$, blocking capacitor, C_{block}, quarter wave transmission line, load capacitor, C_L, and load resistor, R_L.

package chosen for two diodes in parallel to help reduce the semiconductor junction resistance. An output resistance R_L and capacitance C_L form a low pass filter which removes the carrier wave from the output. Furthermore, the quarter wave transformer between the filter and the diodes help to transform the circuit into a full-wave rectifier. An input DC blocking capacitor C_{block} and parallel open circuited matching stub (TL4) help to match the rectenna at a given frequency and power level.

Microwave rectifier impedance matching can prove difficult [6]; the matching depends not only on frequency, but also on input power. The impedance variation of the rectennas is especially important for SPCCs in WSN applications as the power incident on each antenna can greatly vary. This variation can unfavorably load the output and cause additional reflections which can result in substantially reduced energy harvesting efficiency.

IV. SIMULATION AND OPTIMIZATION

Circuit and antenna simulations were conducted using ADS2011.10 and CST, respectively. Rectenna optimizations used the random search method with goals of being matched at 5.8 GHz and 0 dBm input power. The output capacitance and resistance and ideal transmission lines (TL1, TL2, TL3, TL4) impedances and lengths were all variables in this optimization.

A. Single Dipole

Using CST, a single 5.8 GHz half-wave dipole is simulated with a 65 Ohm discrete port source. The realized gain pattern with a S11 of about -35 dB at 5.8 GHz and a -10 dB bandwidth of about 1 GHz. The peak realized gain is 2.4 dB and its impedance is $65 + j2\ \ \Omega$.

B. N^2 Rectenna Array

This case uses 16 identical rectennas as connected in Fig. 3. Using CST, the gain pattern for a single 65 Ω dipole is simulated and used with the Friis transmission equation to find the magnitude and phase of the received power for each antenna as a function of angle for two ranges (0.1 m, 1 m)

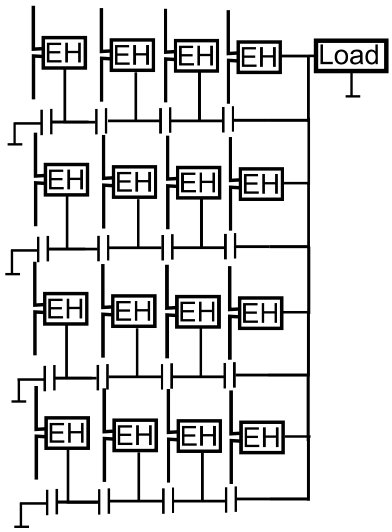

Fig. 4. Schematic of the 16 rectenna array configuation. The final capacitor in each series connection is connected in parallel with the other rows. This connection setup is similar to that of the SPCC, but the SPCC uses sub-arrays instead of series connections of energy harvesting circuitry.

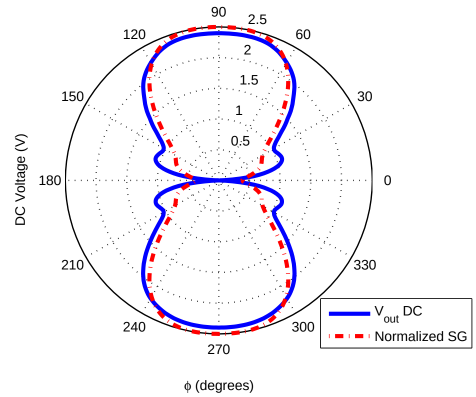

Fig. 5. SPCC DC voltage output of the energy harvesting circuitry for 0.1 m range away from a 36 dBm EIRP transmitter at 5.8 GHz compared to the normalized summation gain of the SPCC. The DC voltage pattern follows the summation gain pattern of the SPCC closely for the near range. The summation gain was normalized to fit the graph of DC voltage output peaking around 2 V.

in free space from a 36 dBm EIRP transmitter. The received power is used by ADS as the rectenna input power level.

The 16 antennas are organized into a square shape similar to the SPCC with rectenna spacing of $3\lambda/4$ as shown in Fig. 4. Each rectenna's output capacitor is arranged in a four series-four parallel configuration across a common load resistor as shown in Fig. 4. Shinohara shows that using a combination of series connections benefits the output voltage [1]. The parallel connections raise the total current on the output and improves the region of near peak efficiency operation over power inputs [7]. With the rectenna outputs arranged in this fashion, all sixteen identical rectennas were optimized in ADS and yielded the results shown in Table II.

TABLE II
RECTENNA OPTIMIZATION DIMENSIONS.

Parameter	N^2 **Rectenna**	**4-by-4 SPCC**
TL1 Length (Degrees)	85.5	131.3
TL1 Impedance (Ω)	115	237
TL2 Length (Degrees)	145.2	95.2
TL2 Impedance (Ω)	175	185
TL3 Length (Degrees)	170.8	178.4
TL3 Impedance (Ω)	182	117
TL4 Length (Degrees)	55.8	73.9
TL4 Impedance (Ω)	45	145
$R_L(\Omega)$	245.6	150
C_L (pF)	100	79.1

C. 4-by-4 SPCC

This case uses the SPCC's 4 sub-array gain patterns from Section II connected to 4 rectifiers all terminated on a common capacitor shown in Fig. 1. In the same manner as before, the RF input power was calculated from each sub-array and used as the input power into each rectenna. In the SPCC case, the antenna sub arrays have an impedance of 16 Ω. The binary feeding structure used for 4-by-4 SPCCs makes the input impedance a fourth of the individual antenna impedance (65 Ω). Using this different rectenna output termination, all 4 identical energy harvesting circuits were optimized with results shown in Table II.

V. DISCUSSION OF RESULTS

The DC voltage result from the output of the SPCC at the range of 0.1 m is shown in Fig. 5 with the normalized summation gain pattern. The DC voltage pattern follows the summation gain very closely. As the range is increased to 1 m, the beamwidth and amplitude of the DC voltage output drops as shown in Fig. 6 and follows the summation gain curve less closely. The deviation from the summation gain curve is due to non-linearity effects from lower power levels as discussed in [8]. This effect is also shown at 0.1 m range at 0 and 180 degrees where the side lobes produce low input power. The 0.1 m range maintains a high voltage level and wide beamwidth over almost 240 degrees of the pattern. The high voltage level over a large beamwidth is exactly why the SPCC should be used in cases of RF energy harvesting without knowledge of the transmitter location.

The 16 rectennas had similar results to the SPCC with a reduced beamwidth compared to the SPCC. In Fig. 7, the peak DC voltage at approximately 3 V is larger than the SPCC's peak voltage, but it is only over the beamwidth of about 60 degrees. The DC voltage gain pattern may seem strange as it appears to be an array pattern, but the antennas are not connected in an array. The results suggest that RF power has leaked thorough the energy harvesting circuitry and reflected off the load. As the reflections and different phases collide, the power converts to DC and is harvested which leads to nulls

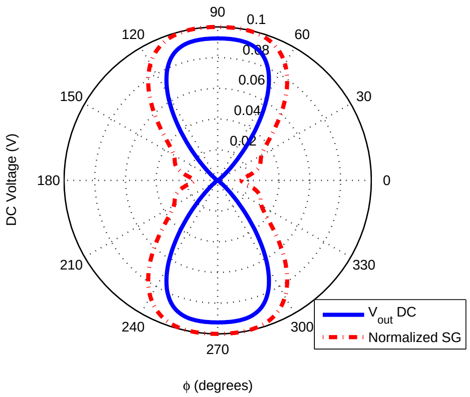

Fig. 6. SPCC DC voltage out of the energy harvesting circuitry for 1 m range away from a 36 dBm EIRP transmitter at 5.8 GHz compared to the normalized summation gain of the SPCC. The DC voltage pattern follows the summation gain pattern only where two sub-array beams of the SPCC overlaid as shown in Fig. 2.

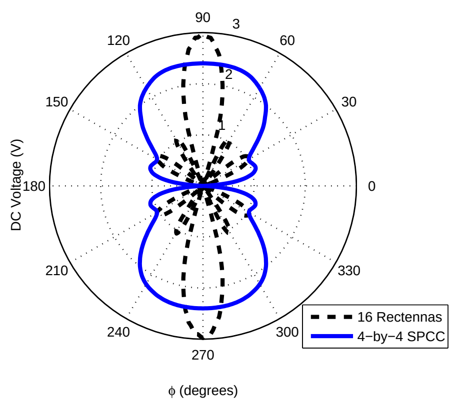

Fig. 7. 16 Rectennas and DC output voltage compared to the DC voltage pattern of the SPCC of the energy harvesting circuitry for 0.1 m range away from a 36 dBm EIRP transmitter.

and peaks in different directions.

As the range increases to 1 m, the beamwidth and the peak gain of the 16 rectenna array drops much lower than the SPCC. The 16 dipoles shows a peak DC voltage at 0.03 V and the SPCC had a peak DC voltage at 0.1 V. The beamwidth difference is also dramatic at 240 degrees versus a meager 20 degrees. The SPCC performs dramatically better in both DC peak voltage and beamwidth for the 1 m range case.

VI. Conclusion

The 4-by-4 SPCC shows DC voltage improvements over 16 rectennas for all cases except peak voltage at 0.1 m range. The benefits of the SPCC increase as the range between the receiver and transmitter is widened. At 0.1 m range, the N^2 rectenna has a peak DC voltage 20% larger than the SPCC, but the SPCC's beamwidth is 400% larger than the N^2 rectenna array. At 1 m range, the SPCC beamwidth is 600% larger, and the peak voltage is 300% larger than the N^2 rectenna case.

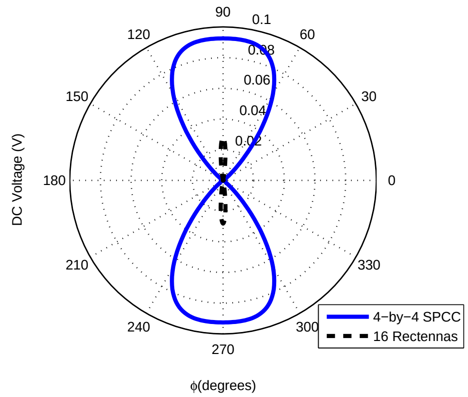

Fig. 8. 16 Rectennas and DC output voltage compared to the DC voltage pattern of the SPCC of the energy harvesting circuitry for 1 m range away from a 36 dBm EIRP transmitter.

The results also show that the summation gain pattern is better at predicting the shape of the DC voltage output for higher power levels than lower power levels when the non-linearites of the didoes distort the DC power pattern. The 16 element array with the 4 series-4 parallel connections have an unexpected DC power pattern result which looks like an array pattern. These results could be explained by RF leakage creating a quasi-array out of rectennas to form a high gain and narrow beam.

In the future, other techniques to interconnect energy harvesting circuitry will be investigated. By using more series or parallel connections, the output DC voltage and beamwidth can be altered for the N^2 rectenna and SPCC case. Overall, the SPCC performed better than the N^2 rectennas in low power conditions. In addition, different SPCC phase offsets can be implemented to aim the sub-array main beams in other directions to improve energy harvesting.

References

[1] N. Shinohara and H. Matsumoto, "Study of Large Rectenna Array for Microwave Energy Transmission," *IEEE Transactions On Microwave Theory and Techniques, Vol. 46, No. 3*, March 1998.

[2] Hagerty, J.A. et al., "Recycling Ambient Microwave Energy With Broad-Band Rectenna Arrays," *IEEE Transactions On Microwave Theory and Techniques, Vol. 52, No. 3*, March 2004.

[3] F. Erez and Z. Popovic, "DC power pattern of Rectifier-Antenna," *2011 URSI General Assembly and Scientific Symposium*, August 2011.

[4] B. R. Marshall and G. D. Durgin, "Staggered Pattern Charge Collector Design and Optimization," *IEEE Radio Wireless Week 2013*, Jan. 2013.

[5] B. R. Marshall and G. D. Durgin, "Staggered Pattern Charge Collection: Antenna Technique to Improve RF Energy Harvesting," *IEEE RFID 2013*, 2013.

[6] Y. Park, D. You, K. Kim, Y. Rhee, "A study on the analysis of rectenna efficiency for wireless power transmission," *1999 IEEE TENCON*, 1999.

[7] P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury, "Design Optimization and Implementation for RF Energy Harvesting Circuits," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems, Vol. 2 No. 1*, March 2012.

[8] M. Almada, L. Blanca-Pimentel, J. Block, J. Gonzalez, C. Valenta, and G. Durgin, "Power Conversion Gain as a design metric for RFID Systems," *2012 IEEE Antennas and Propagation Society International Symposium, pp. 1 . 2*, July 2012.