Staggered Pattern Charge Collection: Antenna Technique to Improve RF Energy Harvesting

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***Abstract*—This paper introduces the theory of N-by-N staggered pattern charge collectors (SPCC) and a methodology to design and optimize SPCCs for maximum energy harvesting efficiency. The SPCC uses multiple sub-arrays to form an aggregate gain pattern for harvesting RF wireless energy more efficiently than a single antenna or a collection of antennas occupying a similar footprint when the transmitter location is unknown.**

I. INTRODUCTION

Wireless RF harvesting has become an important area of exploration for long range RFID and sensing applications, because inductively powered techniques do not work over long ranges [1], [2]. To improve RF energy harvester efficiencies, arrays have been used to create high gains to improve the power received by passive devices, but these arrays have a downside of small beamwidths which result in position sensitivity [3]. The staggered pattern charge collector (SPCC) uses multiple sub-arrays with phase offsets and main beams to not only have a high gain but a larger beamwidth than a single array. This paper is written to demonstrate the theory of how to design an N-by-N SPCC as well as investigate which phase offsets create the most effective energy harvesters.

In order to improve energy harvesting efficiency, many techniques have been used such as [5] which uses a high impedance antenna to ensure the energy harvesting circuitry is activated over a long distance. [6] and [7] alter the energy harvesting circuitry matching and topologies to improve the efficiency of the power conversion, while [3] uses an antenna array to increase the power received into the energy harvesting circuitry. Large arrays of antennas are effective to harvest RF energy efficiently but are limited by narrowing of the main beam which does not occur by using multiple, steered sub-arrays as with the SPCC [4].

The SPCC has many benefits such as increasing the range of long range passive RFID and wireless sensors by inducing higher powers on the energy harvesting circuitry without reducing the effective beamwidth of the antenna system. The disadvantages of the SPCC are the footprint size and complexity of design. The complexity of design has been dramatically reduced by using Ns that are powers of 2 in this paper. Each of the N sub-arrays in the SPCC are designed to aim in different directions to cover the same area as a single antenna but with a high gain due to using sub-arrays. Section II develops the theory behind designing and building N-by-N SPCCs for maximum gain and coverage.

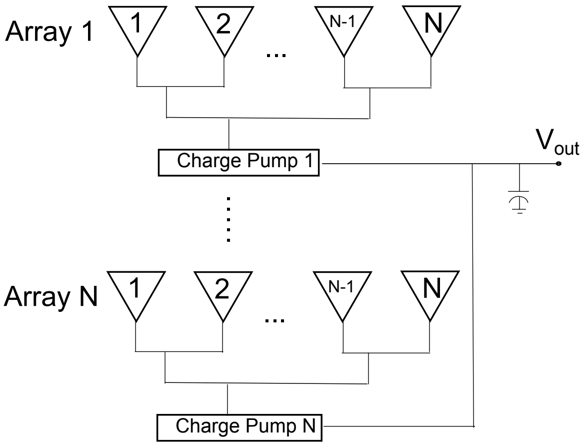

Fig. 1. N-by-N schematic of SPCC showing N sub-arrays each with N antennas. Each sub-array harvests energy through a charge pump or other energy harvesting circuitry, which are all connected to a common capacitor with a DC output of V_{out} .

II. THEORY

The SPCC is composed of N sub-arrays that contain N antenna elements; each sub-array is connected to energy harvesting circuitry terminated on a common capacitor as shown in Fig. 1. With N sub-arrays of N elements, the layout of the SPCC is an N-by-N grid of antennas. Each sub-array has is RF isolated from other sub-arrays allowing each sub-array to have its own main beam. Each sub-array with a smaller beamwidth, higher peak gain than a single antenna is aimed in a different direction to widen the effective beamwidth of the SPCC.

The SPCC can range in sizes from a 2-by-2 to an N-by-N case which is limited to powers of 2 for this paper due to the binary feed structure. The binary feed simplifies the mathematical analysis and design for the SPCC, so each sub-array has $\log_2(N)$ *levels* between the antennas and the energy harvesting circuitry as shown for the 4-by-4 example in Fig. 2.

A. Sub-array pattern

The sub-array is the building block of the SPCC and each must be designed correctly to ensure maximum coverage and gain. The sub-array pattern is formed by using classical linear array theory as shown in (1) where N, number of antennas, W, wave number, d, the distance the antennas are apart, θ, coordinate angle, and β_{nm}, the phase offset for each antenna [8].

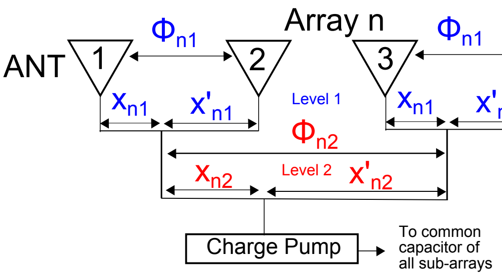

Fig. 2. 4x4 SPCC schematic showing the nth sub-array's parameters for length, levels, and phase shifts with the energy harvesting circuitry terminating on a common capacitor between all sub-arrays.

$$AF_n(\theta,\phi) = \sum_{m=1}^{N} e^{j(m-1)(Wd\cos\theta+\beta_{nm})} \tag{1}$$

$$\beta_{mn} = \gamma_m \begin{bmatrix} \phi_{n1} \\ \phi_{n2} \\ \vdots \\ \phi_{nK} \end{bmatrix} \quad \text{where } K = \log_2(N) \tag{2}$$

$$\gamma_m = \begin{bmatrix} \lfloor (m-1)/N \rfloor \%2 \\ \vdots \\ \lfloor (m-1)/(2^2) \rfloor \%2 \\ \lfloor (m-1)/2 \rfloor \%2 \\ (m-1)\%2 \end{bmatrix}^T \tag{3}$$

Each sub-array uses the binary feed structure which is related to the phase offset for each antenna, β_{nm}, and feed phase offsets, ϕ_{nk}. The phase offsets for each element in each sub-array is defined in (2) and (3) where γ_m is a binary 1-by-K matrix of $m-1$, K is the total number of levels on each sub-array, n is the current sub-array, and m is the current antenna of that sub-array. The modulus (%) and floor function ($\lfloor\rfloor$) are used to mathematically calculate the binary matrix of $m-1$. The use of the binary tree feed makes for simpler linear algebra to find the correct phase offsets of each antenna in each sub-array based on what path is taken through the feed to the energy harvesting circuitry.

An example for the 4-by-4 SPCC is expressed mathematically for the layout shown in Fig. 2 with 4 antennas and 4 sub-arrays. By using symmetry, only four phases offsets need to be used to define all the SPCC lengths since the top two sub-array offset lengths are the inverse of the bottom two. In addition, the 4-by-4 SPCC has 2 levels of binary feed structure for each sub-array with each having the specific phase shift (ϕ_{nk}). For the 4-by-4 example, the nth sub-array of the SPCC antenna phase offsets can be found with (4), and (5). These phase offsets are used to find the offset lengths of the SPCC in Section II-D.

$$\beta_{nm} = \gamma_m \begin{bmatrix} \phi_{n1} \\ \phi_{n2} \end{bmatrix} \tag{4}$$

$$\gamma_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}^T \tag{5a}$$

$$\gamma_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}^T \tag{5b}$$

$$\gamma_3 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}^T \tag{5c}$$

$$\gamma_4 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}^T \tag{5d}$$

B. Design Equations

Each SPCC sub-array has levels, K, each level ,k. of each sub-array has phase offsets, ϕ_{nk}, as previously shown in Fig. 2. Also shown in Fig. 2 are the offset lengths, x's, which can be found directly from the phase offsets and distance between antennas, d, with (6) and (7).

$$2^{k-1}d = x_{nk} + x'_{nk} \tag{6}$$

$$\phi_{nk} = \frac{2\pi f}{v_p}(x_{nk} - x'_{nk}) \tag{7}$$

By using these equations, the offset lengths for each junction can be found for the fabrication of an SPCC. The length offsets, x_{nk}, are the lengths required to build the binary feed array out of transmission lines and are determined by solving (6) and (7). In addition to these offset lengths, it is necessary to use microwave impedance matching for the antennas and the feed structure, but this is outside the scope of this paper. One possible impedance matching structure could be similar to the split T power divider shown in [10].

C. Aggregate Gain Pattern

The SPCC does not have a traditional gain pattern since it is a collection of sub-array patterns. By assuming that only *one* sub-array with the largest gain is harvesting at any instant in time, an *aggregate gain pattern* is determined. The assumption that only one sub-array is active at a time is used because given an angle of incidence, only one sub-array main beam will be at this angle. If multiple sub-arrays have overlapping main beams, this is no longer a valid assumption. The aggregate gain pattern is defined as the maximum of the superposition of all the sub-array patterns as shown in (8) and (9) and can be visualized in Fig. 3. The gain pattern of each array is G_n, the antenna gain pattern is $G(\theta,\phi)$, the array factor of each array is AF_n, and AG is the aggregate gain pattern which approximates the pattern for the entire SPCC.

$$G_n(\theta,\phi) = G(\theta,\phi)|AF_n(\theta,\phi)|^2 \tag{8}$$

$$AG(\theta,\phi) = \max\left(G_1(\theta,\phi), G_2(\theta,\phi), \ldots, G_N(\theta,\phi)\right) \quad (9)$$

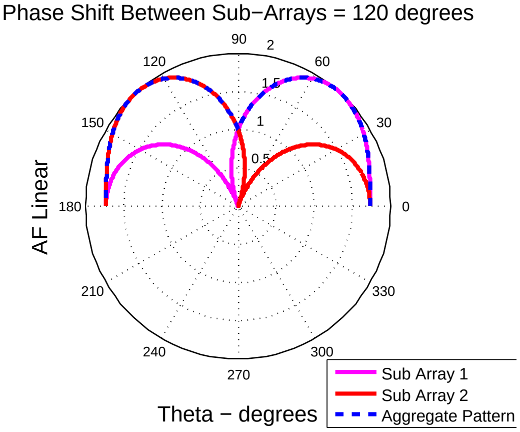

Fig. 3. Aggregate array factor pattern for 2-by-2 SPCC. Sub-array 1 has a larger lobe on the left half, but sub-array 2 has a larger lobe on the right half. The aggregate pattern uses the larger lobe from both sub-array patterns.

D. Optimization

With the aggregate gain pattern defined, the next step is to optimize the aggregate gain pattern for energy harvesting. Since energy harvested is directly proportional to the square of the inputted voltage amplitude, the optimal SPCC must have a high gain to increase the input voltage amplitude [13]. In addition, the direction of incidence of the wireless signal is unknown, so, ideally, the aggregate gain pattern would have a high gain in all directions.

$$IPCG = \int_{BW} AG(\theta,\phi) \quad (10)$$

Given an N-by-N SPCC, the values of ϕ_{nk} can be varied from 0 to 180 degrees to maximize the gain and beamwidth. To obtain an optimal result for gain and beamwidth, the metric of *integrated power conversion gain* (IPCG) must be introduced [9]. IPCG is the integration of the aggregate gain over the beamwidth of the pattern as shown in (10). By maximizing the IPCG, a function of beamwidth and aggregate gain, the goal of a high gain and large beamwidth can be achieved.

The claim that this value should be conserved as beamwidth changes due to basic array theory is invalid, because this is an aggregate gain pattern formed by multiple sub-arrays and not a traditional array pattern. This metric can be used to compare antennas or antenna arrays for effectiveness in ambient RF energy harvesting, but does not evaluate the antenna system to energy harvesting circuitry matching or energy harvesting circuitry efficiency.

E. Energy Harvesting Equations

The SPCC uses a high gain to increase the amount of power into the energy harvesting circuitry to improve overall efficiency. The basic link budget (Friis' Equation) is given below in (11) with the received gain from a single direction, θ_i,ϕ_i, and the energy conversion equation is given in (12). The power received by the antenna, P_r, is a function of the transmitted power, P_t, gains of transmitter and receiver, $G_{t,r}$, wavelength, λ, and distance between transmitter and receiver, R. The DC power output of the energy harvesting circuitry, $P_{out,DC}$, depends on the efficiency of the energy harvesting circuitry, η_{EH}, reflections of the energy harvesting circuitry, Γ_{EH}, and the received power, P_r [13].

$$P_r = \frac{P_t G_t G_r(\theta_i,\phi_i)\lambda^2}{(4\pi R)^2} \quad (11)$$

$$P_{out,DC} = \eta_{EH}(1 - |\Gamma_{EH}|^2)P_r \quad (12)$$

For energy harvesting applications in most RFID systems, the angle of incidence from the transmitter, θ_i, ϕ_i, is unknown since the location of the transmitter is unknown. The DC power produced at the tag from the unknown transmitter can be determined from (11) and (12) and shows that a high receiver gain in every direction is ideal. Since the SPCC is capable of producing a high gain in multiple directions, the DC output is increased from any given a random angle of incidence in the effective SPCC beamwidth. If a traditional array is used, the transmitter's incidence on the harvester is more likely to be outside the main beam making the array ineffective.

F. Comparison to N^2 Antenna Harvesters

A group of N^2 antennas each with an energy harvesting circuit can be compared to an SPCC since both use the same footprint [12]. Arrays increase the range of wireless power but suffer from a reduced beamwidth [11]. The SPCC benefits from the array gain over a single antenna which allows for the energy harvesting circuitry to work over a farther range, but by aiming the main beams of each sub-array, the reduced beamwidth disadvantage is mitigated.

The SPCC is able to receive wireless power from a farther distance than N^2 single antennas and does not lose coverage like large arrays [4]. A large array can harvest the most energy if the transmitter's location is known via a large array, but in most cases for wireless sensors, the transmitter location is unknown and outside of the main beam making it a poor energy harvester. Overall, the SPCC uses a similar footprint as N^2 rectennas, but by using the SPCC sub-arrays, the SPCC is capable of producing a higher DC voltage at a farther range.

III. SIMULATION AND COMPARISON

A. Aggregate Gain Optimization

Since the SPCC can be implemented with any antenna, a general optimization for gain and beamwidth is not possible, but a general case of an ideal isotropic antenna can be optimized by using IPCG and altering the distance between elements, d, and phase offsets, ϕ_{nk}. In Fig. 4, the IPCG is calculated for multiple antenna separation distances, d, with varying phase offsets between the antennas for the 2-by-2 SPCC.

The optimum value occurs when the distance between the antennas and phase offset is zero as they radiate in all directions at a high gain but this is not possible in actuality since the two antennas would be occupying the same space. The discontinuities in the graphs are due to the resolution of the pattern (5 degrees) and the integration beamwidth changing which is defined as half of the peak of the aggregate gain pattern (3dB bandwidth). Traditional array theory states that antennas separated by a half wavelength create the maximum broadside gain, but in the SPCC, separating the antennas by more or less distance may improve the beamwidth or aggregate gain. Since the distance between the antennas has a dramatic effect on IPCG, when optimizing each N-by-N array, it is important to not only vary each phase offset but also the distance between antennas.

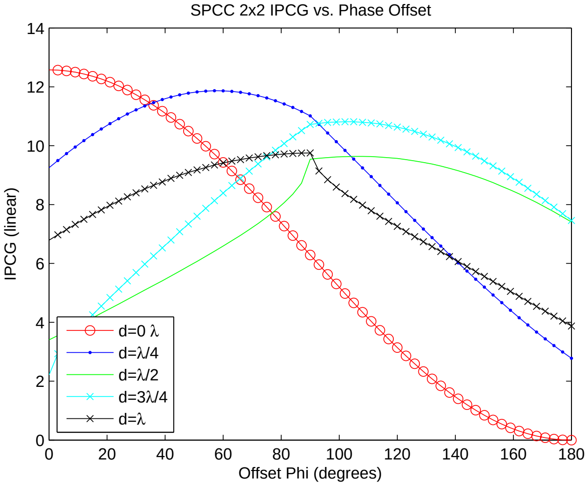

Fig. 4. IPCG for 2-by-2 SPCC with varying phase offset, ϕ_{nk}, and distance, d, between antennas. The IPCG peaks for each separation distance between radiation elements at different phase offsets, ϕ_{nk}

Overall, both the 0 and $\lambda/4$ distance may have mutual coupling effects on each other, so the optimal, practical case to use for design is when the antennas are separated by $3\lambda/4$. As the phase offset is varied, the IPCG increases as the two seperate main beams create a larger effective beamwidth, but, eventually, the main beams aim too far apart. When the beams are aimed too far apart, coverage is lost and the IPCG declines. The peak of the IPCG for each element spacing is the optimal SPCC for the isotropic antenna.

Table I summarizes the 4-by-4 SPCC maximum IPCGs which were found by varying the phase offsets, ϕ_{nk}, with a few different distances between the antennas as done with the 2-by-2 case. The 2-by-2 case maximum IPCGs are also shown in Table I. The benefits from jumping from a 2-by-2 to a 4-by-4 is dramatic since the maximum gain increases by 16 times, but the footprint is increased by a factor of 4. In addition, with four sub-arrays, more main beams are used to create a larger effective beamwidth. By using the phase offsets given, each of the patterns can be recreated and the IPCGs calculated. The 2-by-2 case used steps of 1 degree and the 4-by-4 used steps of 15 degrees for the phase offsets.

TABLE I

MAXIMUM IPCG COMPARISON FOR 2-BY-2 AND 4-BY-4 VARYING ϕ_{nk} (DEGREES) AND d

SPCC	d=λ/4	d=λ/2	d=3λ/4	d=λ
2x2	12.1	9.9	11.1	9.9
ϕ_{11}	59	113	97	76
4x4	44.75	35.82	38.8	36.05
ϕ_{11}	105	180	105	120
ϕ_{12}	90	15	120	120
ϕ_{21}	0	120	15	30
ϕ_{22}	15	90	180	0

After finding the maximum IPCGs and the phase offsets required for each distance between the antennas for the 2-by-2 and 4-by-4 cases, the aggregate gain patterns were plotted as show in Fig. 5 and Fig. 6. These figures show how using the SPCC can create strange but effective aggregate gain patterns for energy harvesting. The larger 4-by-4 SPCC array has more coverage due to more lobes and the element separation distance affects the extremity of the nulls and the broadness of the lobes. For even SPCCs, many aggregate gains have a null in the middle of the coverage due to the symmetry of the SPCC design, but this flaw can be mitigated by using non-symmetry phase offsets, which will be investigated in the future as shown in the plots.

B. Hardware Design for Feed Structures

The theory and optimization technique has been fully explained but how to implement these results has yet to be determined. Two techniques for implementing an SPCC will be discussed: one using two-layer boards and the other using four layer boards.

If a two layer board is used, the traces are implemented exactly how they are shown in Fig. 7 with traces and antennas on the top layer and a ground plane on that bottom. The two layer technique is simpler but has currents running close the antennas that can alter the wave formation. The energy harvesting circuitry also needs to be on the top level, which could disrupt the forming of the SPCC's fields.

For the four layer feed structure, the two middle planes are both ground while the bottom layer has the SPCC antennas and the top layer has the traces that connect to the antennas through a via. The four layer technique fully isolates the antennas from the currents of the feed and energy harvesting circuitry. The four layer board also has more room for a more complicated feed structure. The binary feed structure discussed in this paper can be done on either two or four layer. Other interesting feeds will be explored in the future for non-powers of two such as the 3-by-3 case.

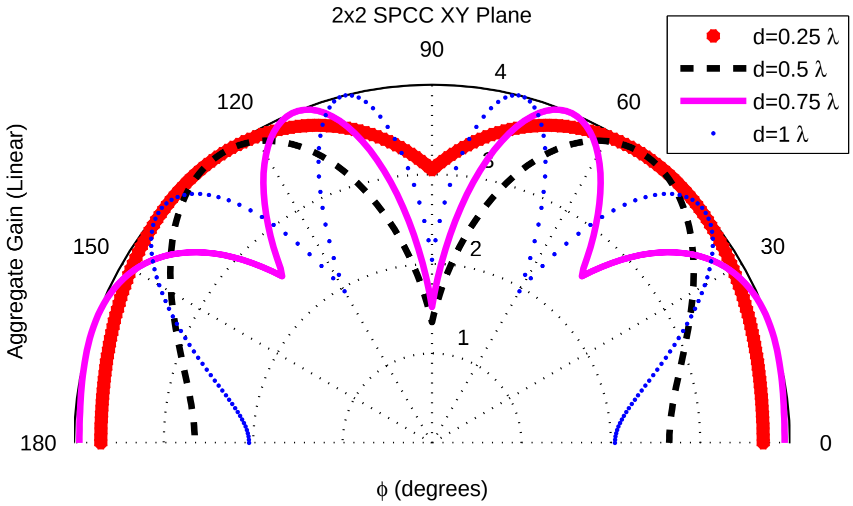

Fig. 5. Aggregate Gain Pattern with Maximum IPCG for 2-by-2 SPCC while varying element separation distance d

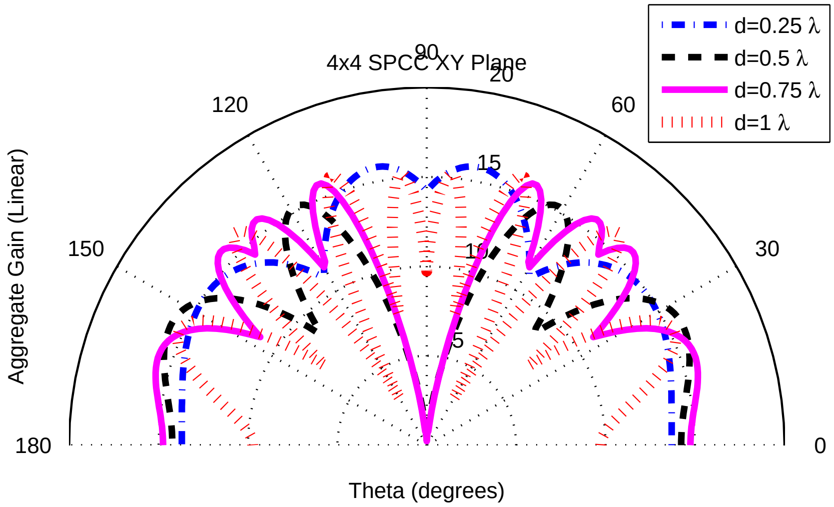

Fig. 6. Aggregate Gain Pattern with Maximum IPCG for 4-by-4 SPCC while varying element separation distance d

C. Simulation with Patch Antennas SPCC in Full Wave Solver

For the full wave simulation results, a patch antenna resonant at 5.8 GHz was used in a 4-by-4 SPCC and the phase offsets of $\phi_{11} = 170, \phi_{12} = 110, \phi_{21} = 140, \phi_{22} = 90$ and the elements separated by $3\lambda/4$. Fig. 8 shows the aggregate gain pattern and its improvements in gain over the single patch gain pattern. The higher gain results in higher power entering the energy harvesting circuitry which increases the DC voltage output.

The peak gain for a 5.8 GHz SPCC of patches is about 10 dBi versus 7 dBi for the basic patch and the half power beamwidth increases for the SPCC from approximately 90

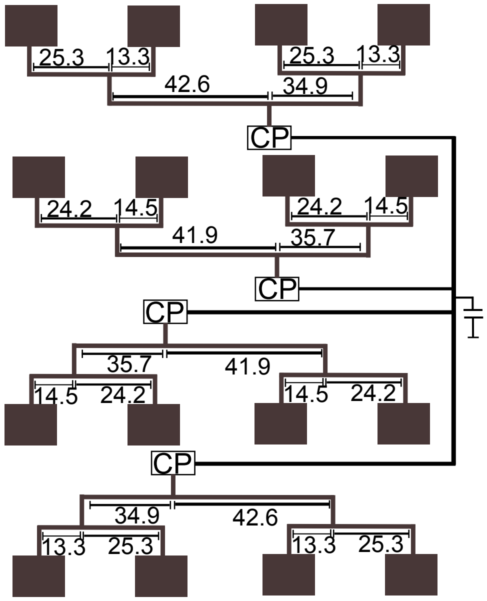

Fig. 7. This is an example of a 4-by-4 SPCC layout for a two layer board with patch antennas at 5.8 GHz. All the length offsets are identified for $d = 3\lambda/4$ and $\phi_{11} = 170, \phi_{12} = 110, \phi_{21} = 140, \phi_{22} = 90$. All units are in millimeters.

degrees for the patch to 120 degrees. A negative of this SPCC is the null in the middle of the pattern that results from the symmetry of the SPCC as previously discussed but can be reduced by changing the distance between elements or phase offsets.

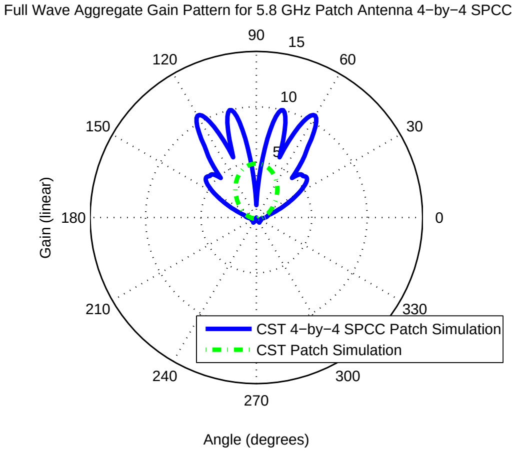

Fig. 8. CST patterns for the single patch used in simulation and a 4-by-4 SPCC of patches with $d = 3\lambda/4$ and $\phi_{11} = 170, \phi_{12} = 110, \phi_{21} = 140, \phi_{22} = 90$. The gain and half power beamwidth is improved with the SPCC but uses a larger footprint and has a null in the middle of the pattern.

IV. CONCLUSION

This paper has developed the mathematical theory of the N-by-N SPCC with a binary feed and has shown design equations for fabrication. This methodology can be applied to produce various sized SPCCs for energy harvesting solutions with long range wireless applications without knowledge of the transmitter's location.

The SPCC uses multiple sub-arrays to create an aggregate gain pattern that has both a high gain and wide beamwidth. It is better than a single array because it has a wider beamwidth and improves the gain higher than a single antenna. The disadvantages of the SPCC include a larger footprint and complexity of design that has been simplified by this paper. For practicality, a CST simulation with a 4-by-4 5.8 GHz patch SPCC was shown with similar results to those predicted by the theory.

SPCCs are not limited to linear arrays; for example, The SPCC could use four 2-by-2 sub-arrays aimed in different directions to create a larger effective beamwidth. Another example is to use a reconfigurable antenna with multiple energy harvesting circuits attached to form multiple main lobes for harvesting.

In the future, other sized SPCCs should be investigated; specifically, the 3-by-3 since it does not dramatically increase the footprint but increases the peak gain. By using the SPCC in conjunction with other energy harvesting optimization strategies such as charge pump optimization, longer range passive wireless systems are possible.

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