RF Energy Harvesting with Multiple Antennas in the Same Space

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Abstract

It is highly desirable to increase the amount of energy derived from a given space by an energy-harvesting device. In this paper, multiple energy-harvesting antennas in essentially one space or area are proposed and experimentally studied as a means to increase the energy or power/area ratio. Four cooperating antennas are proposed in a square area that is less than twice the area required for a single antenna. The results obtained suggest that this can be a very promising method for energy harvesting.

Keywords: Antennas; energy conversion; RFID; energy harvesting

1. Introduction

Radio frequency identification (RFID) is believed to be a technology that may replace bar codes at some point in the future [1]. An RFID tag typically consists of a CMOS chip (die) and an antenna, with some relatively simple means of connecting the antenna to the chip. The chip is powered by harvesting some of the incident RF energy. The communications are implemented by changing the impedance of the load to modulate the RF wave backscattered or reflected from the tag's antenna, which is processed by a remote receiver. This is referred to as a passive (no onboard energy source) backscatter tag or technology. One of the difficulties with the backscatter technology is that the surface on which the tag is placed may reflect a large amount of the unmodulated incident RF wave back to the receiver, and thus "wash out" the modulated wave from the RFID tag.

An alternative technology/methodology has been developed [2], where the energy from the typical source powering the RFID is converted to a dc voltage by an antenna/matching circuit/charge-pump combination. This alternative technology/methodology has been given the name of *active remote sensing* (ARS), and can be evaluated for effectiveness and feasibility as described in [3]. The energy is then used to power a processor/transmitter/antenna combination that transmits the identification (and possibly other information, e.g., from a sensor) to a receiver at a different frequency. The active remote sensing signal-to-noise ratio (SNR) at the receiver is obviously much more favorable than with the backscatter technology. However, the cost of the more favorable SNR ratio is the requirement for more energy to operate the circuitry on the tag or sensor. Backscatter RFID requires connecting a silicon die (chip) to an antenna, which makes the resulting RFID tag too expensive for the most-desired applications. Current active remote sensing research is directed towards including all elements on a single silicon die or chip [4].

In either backscatter or active remote sensing, the area of the tag or silicon die is expensive. It has been found [3, 4] that a square spiral antenna is effective in the antenna/matching circuit/charge pump combination. In addition, it has been observed that the conductor width and spacing can be varied to some extent without seriously degrading the performance, measured as the dc output voltage of the charge pump, and this is the basis of this article. *Given a fixed surface (physical) area, can multiple antennas be placed in the conductor spacing and improve the performance in terms of total output voltage by combining the multiple-antenna/matching-circuit/charge-pump combinations connected to provide a single source?* There are thus two issues: (1) the functionality of the multiple individual combinations in essentially the same physical area for increasing the total energy harvested, and (2) the connection of the multiple combinations as a single source of dc energy.

As indicated previously, the energy harvesting mechanism is an antenna/matching-circuit/charge-pump combination. Thus, it is necessary to match the impedance of the antenna to the impedance of the input of the charge pump, which is typically on the order of 1 K ohm, real. Therefore, traditional matching [5] does not work, as such. However, the "optimum match" occurs at the point where maximum energy is obtained at the charge-pump output in terms of the dc voltage produced.

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2. The Road to Silicon

The ultimate goal of the reported research is the improvement of on-chip (silicon-die) energy harvesting. Experimentation with silicon dies is expensive and time consuming, costing thousands of dollars per prototype, with a two-to three-month turnaround time. Thus, it is important to analyze as many factors as possible using less expensive and quicker prototypes. The close proximity and generally inaccessible nature of a silicon die make it very difficult to measure many in-situ parameters. For example, while it is possible to provide access to certain measurement points by bringing conductors to an accessible pad on the die, such a path introduces L and C parasitics that inaccurately characterize the actual voltage characteristics at the in-die node. Extraction software for a chip layout is very helpful for digital circuit evaluation, but such software is less than capable of providing parameter values that can be used, for example, in achieving a matching condition between the antenna and the load.

It is thus important to glean as much information from macro-size experiments, which can be analyzed in terms of relative effects so as to focus on factors that can be isolated more easily from a prototype die, involving circuitry and physics that do not dominate the classical digital CMOS world. Given the relative effects, it is much easier to scale to the absolute scale, although considerable caution must still be exercised in the scaling process.

In order to enhance the energy harvested at the charge-pump output on both CMOS chips and small printed circuit boards, a number of ad hoc empirical approaches have been found to be successful. The technique reported later in this paper has been found to be successful for the purposes of harvesting energy through charge pumps to obtain the maximum dc voltage. The impedance matching between the individual antennas and the corresponding individual charge pumps for each antenna/charge-pump combination was experimentally performed on the basis of maximizing the dc voltage output. The goal of the multiple antennas in a given area was to overcome the reduced efficiencies of the pragmatic antenna/charge-pump combinations by employing as many antennas as practically possible in a fixed physical area where the individual harvested energies can be summed. The antennas will be scaled to the size of the die. The primary focus here was to understand the relative effects in the macro world, before trying to scale to the micro world.

Although it is difficult to fabricate multiple antennas in exactly the same physical area occupied by a single antenna, it is possible to fabricate multiple antennas in a physical area somewhat larger than the physical area of a single antenna. In the current example, four antennas will occupy the physical area of slightly less than twice that of a single antenna.

The mutual orientation and shape are the other parameters to be investigated, based primarily on the ability to intertwine the conductors. While this is certainly an avenue of research, at this time, only the shapes shown in Figure 1, with the orientation shown in Figure 2, have been the object of serious experimentation, primarily because this has solved the initial problem with an increase of $4.0/1.83 = 2.18$ in space utilization. The increase in the amount of energy harvested with respect to physical area is referred to here as a *utility factor*. This is certainly an area of future research.

It is important that the area involved not be confused with the effective area [5] of the antenna. However, it is interesting to note that based on the energy harvested by the single antenna of Figure 1 and the attendant effective area of that antenna, the lack of degradation of the energy harvested implies that there is an overlap of effective areas signified by the utility factor. This implies an "increased efficiency" in the use of the given energy (or power) density for a given transmitted energy (or power). Consider a physical two-dimensional area, A, and an antenna with an efficiency to harvest x percent of the total energy at a given frequency available in area A. The goal of the multiple antenna strategy is then to construct x/A antennas in the physical area, A, to harvest all of the available energy at the specified frequency.

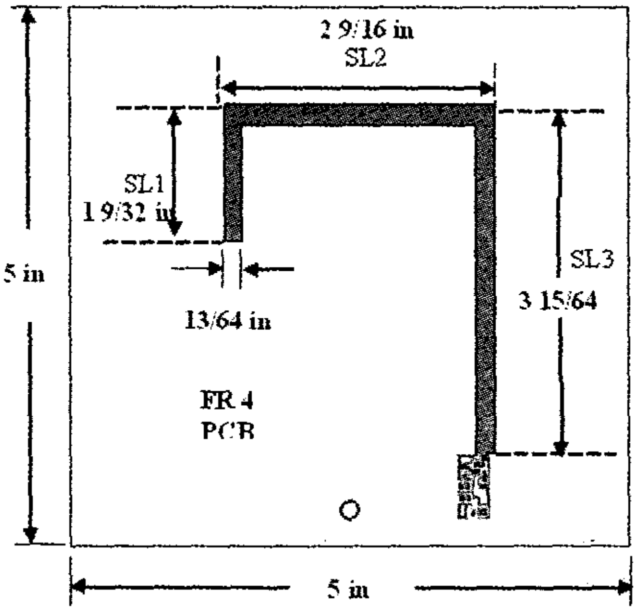

Figure 1. The layout of the single-antenna board (Board 1).

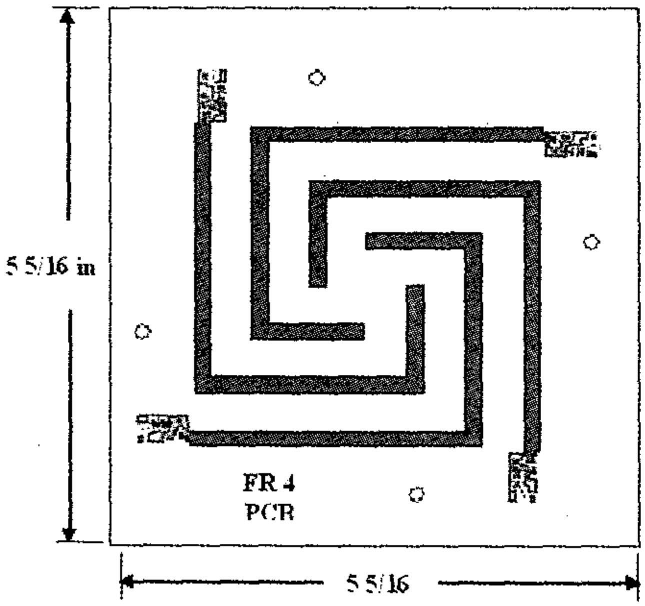

Figure 2. The four-antenna board (Board 3) layout.

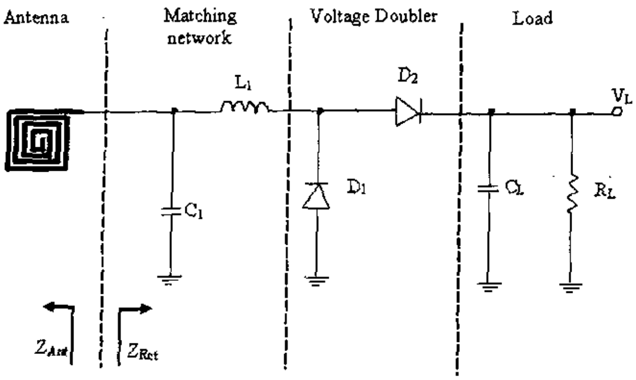

Figure 3. A schematic of the RF front end.

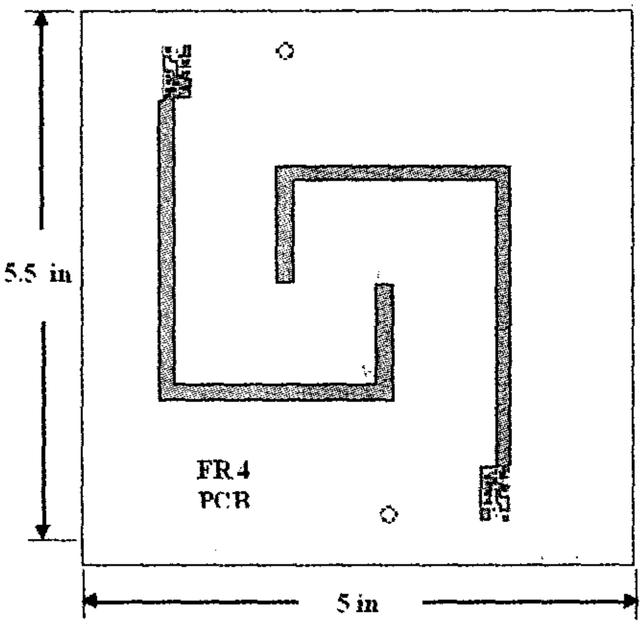

Figure 4. The double-antenna board (Board 2) layout.

3. Antenna Design and Layout

The energy-harvesting antennas used in this research were fabricated on FR-4 substrates, using printed circuit board (PCB) technology. The substrates were 1.5 mm thick, and had a relative permittivity of 4.4. The metal antenna structures were built on the top copper layer, which was 40 μm thick. There were no ground planes directly underneath the antenna structures. The antenna was connected to a load circuit through matching circuitry forming what can be viewed as an asymmetric dipole [7]. Thus, the apparent monopole (half of a dipole) antenna did not require a ground plane.

The basic antenna structure and dimensions are shown in Figure 1. It was a square spiral, with the innermost terminal open and the outermost terminal connected to the load. The load in this case was the charge pump/voltage doubler, which provided a dc voltage at the output. In turn, the load on the dc voltage was typical electronics, in this particular case consisting of a microprocessor, a thermister, an A/D converter, and an RF transmitter. In summary, the load was the charge pump pictured in Figure 3 with the microprocessor, thermister, A/D converter, and RF transmitter constituting what is identified as R_L in Figure 3.

The physical size of the load circuitry can be seen attached to each of the antennas in Figures 1, 2, and 4. The actual dimensions were 9/32 in by 9/16 in. The spiral was designed in such a way that the length of its outermost segment was equal to a quarter of a wavelength, and the overall length of the three segments was equal to half of a wavelength. As can be seen from the area of the circuit in Figures 2 and 4, the monopole length of the asymmetric dipole contributed by the functional circuitry was relatively short. For the operational frequency of 915 MHz, the specific lengths for the three segments of an antenna were $SL1 = 1/12\,\lambda = 27.3\,\text{mm}$, $SL2 = 1/6\,\lambda = 54.6\,\text{mm}$, and $SL3 = 1/4\,\lambda = 82.0\,\text{mm}$. The metal trace width, W, was 5 mm.

In order to determine the effectiveness of locating multiple antennas in the same space, three PCBs, with one, two, and four antennas with essentially the same overall dimension of FR 4, were fabricated. Their layouts were as shown in Figures 1, 2, and 4, respectively. The basis of the three boards for testing was to compare the effect of a single antenna operating without any proximate antennas. The same was true for the two antennas in the proximate locations of other antennas, or as two antennas acting without additional antennas. The results of the testing supported the lack of an effect of the proximate antennas.

4. Measurement Setup and Results

The illustration of the measurement setup for the testing is shown in Figure 5. A stable electromagnetic field was created by a linearly polarized square patch antenna connected to a 5 W constant wave source. The RF source consisted of a Hamtronics® [8] 915 MHz exciter, feeding a Motorola MHW 812A3 single package amplifier. These, in turn, fed a square patch antenna (5 21/32 in by 5 21/32 in) with a square ground plane (8 in by 8 in), with a feed through an N-type connector to a point centered 5/8 in from the top edge of the copper patch. The patch-ground plane separation was 3/4 in. The output of the amplifier was 5.5 W, and the gain of the patch antenna was 6.

The antenna under test was placed in the field for the test measurement. All measurements were conducted in a non-anechoic laboratory environment. With the RF source unpowered, all dc output readings from the charge pumps were null. A curve of the available power at the load provided by the antenna versus its distance from the transmitting antenna was obtained when it was moved along a sliding table, as indicated in Figure 5.

In order to avoid the possible effects of cable connections on the measurement accuracy, the RF power available from each

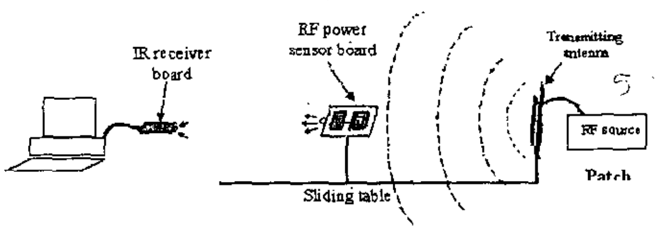

Figure 5. A schematic of the measurement setup.

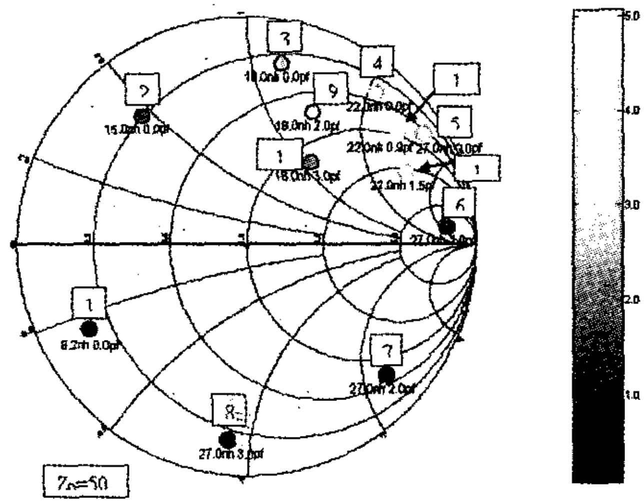

Figure 6. The annealing approach to impedance matching for energy harvesting.

antenna was first converted to a dc voltage on a 1K Ω resistive load by a dedicated voltage doubler connected to the outermost terminal of the spiral. The dc voltage on the resistive load was then digitized, framed, and transmitted through an infrared (IR) link to a PC, where the data were analyzed and stored by a detachable measurement module. Using previously obtained calibration data for the RF-dc converter, the dc voltage could be converted back into an equivalent RF power available from the antenna.

An *LC* matching network was inserted between the antenna's terminal and the voltage-doubler circuit, giving the front-end circuitry the circuit shown in Figure 3. As mentioned previously, the *LC* network matched the antenna's impedance to the charge-pump's input impedance solely on the basis of maximizing the charge-pump's dc output voltage. The diodes in the charge pump were Agilent HSMS2820 surface-mount devices, and the *L* and *C* were 0603-type SM packages, with values varying according the matching summarized in Figure 6. R_L and C_L were the input resistance, with R_L on the order of 1 K Ω, and C_L having an insignificant value at the 915 MHz energizing frequency.

Using an annealing approach [9] for obtaining the optimum antenna-to-load matching, an optimum match between the antenna and the load, and thus maximum power transfer, could be achieved even without prior knowledge of the antenna's impedance. The reason for making a point of the lack of prior knowledge regarding the antenna's impedance is simply that under many conditions of energy harvesting, the space, conductor, point of connection, etc., are functions of an attached device or enclosure specifying the antenna's physical parameters, leading to numerous innovative ad hoc arrangements, as opposed to a traditional antenna design. Thus, whatever "fits" needs to be matched to the charge-pump's input impedance.

The annealing approach is a procedure whereby various sets of inductor and capacitor values are used as matching elements, where the resulting energy harvested is measured for each *LC* combination. The input impedance of the RF-dc converter with the matching network is plotted as a point on a Smith chart, with a color coding for the amount of energy harvested, as shown in Figure 6. After a number of tries, it is easy to see the clustering of the color-coded points and to selectively choose other points to achieve a near-optimum value. Figure 6 illustrates a number of points showing the results on a Smith chart. It is important to note that the matching achieved in this manner tends to optimize this asymmetric-dipole [7] configuration. The matching component values are indicated in Figure 6 as circles on the Smith chart, with grayscale indications of voltage at the charge-pump output as compared to the 0 to 5 V grayscale on the right of the figure. Note that point 12 is 5.0 V, and point 8 is < 1.0 V.

The energy (power) available from each antenna on the three boards was measured one by one, using the setup described previously. The object of this research was to determine if multiple antennas in very close proximity could be used to harvest energy proportional to the number of antennas, at least up to four, compared to a single antenna. To test this hypothesis, three PCB boards of the same form, containing one, two, and four antennas, as shown in Figures 1, 2, and 4, were fabricated. The first test was to compare the energy harvested by a single antenna as a benchmark for the multiple-antenna comparison. This test would also indicate any obvious interactions of the additional antennas with the antenna under test in the two and four antenna cases. The

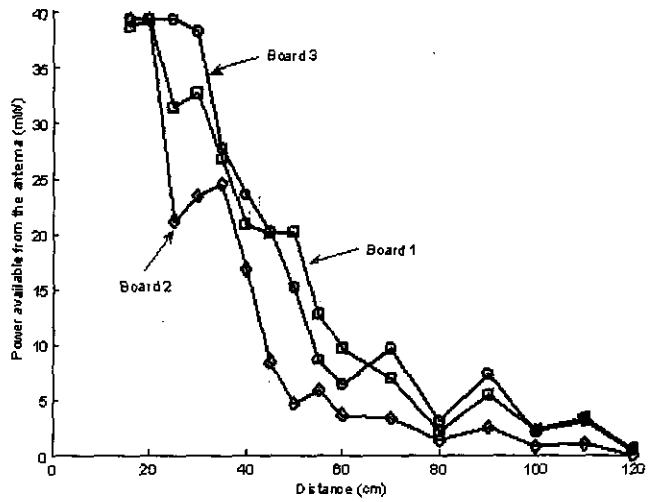

Figure 7. The power available from each antenna on the three different boards.

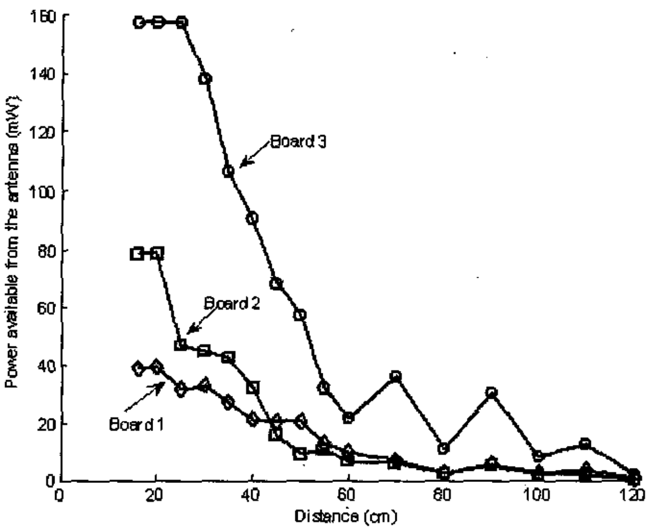

Figure 8. The total amount of power available from the three boards.

results of the energy harvested from a single antenna are shown in Figure 7. As can be seen from Figure 7, all three single-antenna cases were essentially equivalent, showing no differences in these particular cases.

As can be seen from the results illustrated in Figure 7, the energy-harvesting ability of a single antenna without other antennas (Figure 1), proximate to one other antenna (Figure 4), or proximate to three other antennas in the four-antenna configuration (Figure 2) was essentially the same. This result indicated that the inner antenna coupling was rather small. The total amount of power available from each board is plotted in Figure 8.

As indicated in the Introduction, there are two issues to be addressed in this paper: (1) can multiple antennas occupying essentially the same physical area harvest more energy that a single antenna in the same area, and (2) can these multiple energy sources be efficiently combined into a single source?

The ideal case for comparison would have been for all antennas to occupy the same identical space. However, if all of the antennas were of the same physical dimensions and shape as that of Figure 1, it would have been physically impossible to fit them into exactly the same area in the same plane. Thus, some space was lost in keeping the antennas and the associated circuitry from actually touching each other. The four antennas shown in Figure 2 represented one method of locating four such antennas in close proximity. As pictured, the area of the four antennas was 2.84 times that of a single antenna. If the four antennas were placed as close together as possible without physically touching, the area required to fabricate these four would have been 2.72 times the single-antenna area. Thus, a factor of an additional $\left[(2.84-2.72)/2.72\right]\times 100 = 4.41$ of additional area was used to allow some separation for the conductors and associated circuitry.

Figure 8 addresses the first of these two issues, where Board 1 indicates the total energy harvested by a single antenna, Board 2 was the total energy from two antennas, and Board 3 was the total energy from the four antennas. These represented about 80 mW, 155 mW, and 320 mW, respectively, at a distance of 20 cm from the RF source antenna. The answer was "Yes." The results for the two- and four-antenna combinations were obtained by algebraically summing the power available from each individual antenna, as shown in Figures 9 and 10.

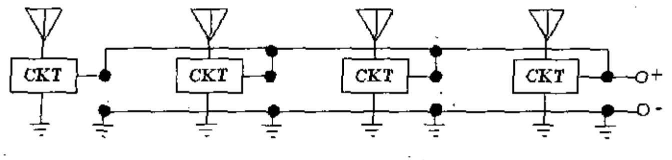

Figure 9. The parallel connection (CKT is the series combination of the matching network, voltage doubler, and load of Figure 5).

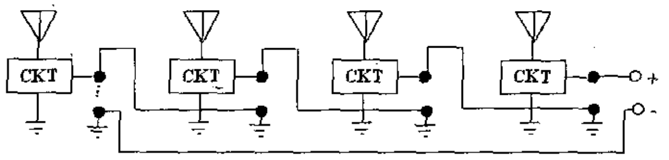

Figure 10. The series connection (CKT is the series combination of the matching network, voltage doubler, and load of Figure 5).

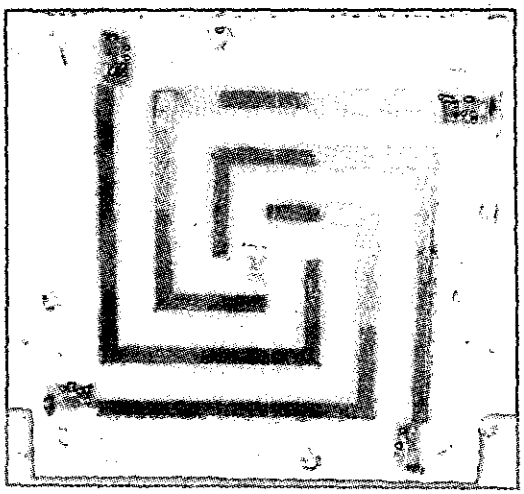

Figure 11. A photo of the printed circuit board with four antennas in the same space.

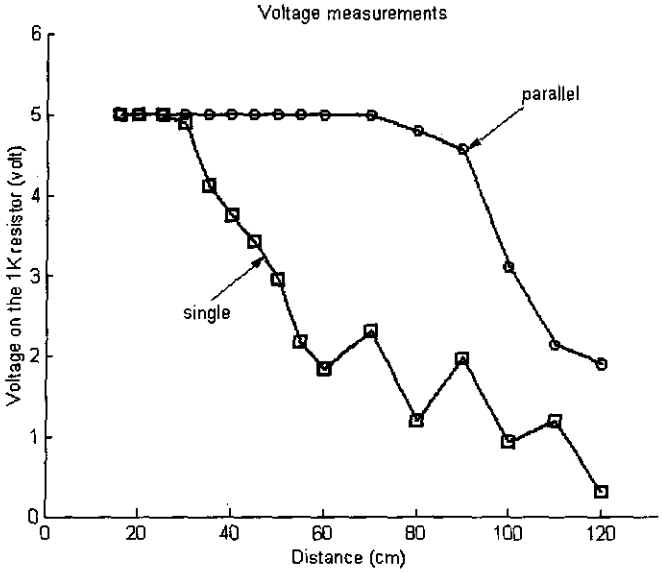

Figure 12. The voltage responses for combined outputs.

From Figure 8, it is easy to see that the amount of power that was available from one individual antenna on the three boards was similar. The general area normally occupied by the single antenna in Figure 1 was typically considered to be that area bounded by the elements that form the antenna. The total area occupied by the four antennas was not exactly the same area as a single antenna. The four-antenna area was 1.83 times the single-antenna area (measured at the border). As the number of antennas on the individual board increased, there was a corresponding increase in the total amount of available energy. In the experiments, the power was increased by a factor of four while the area was increased by the factor of 1.83. Thus, for an 83% increase in area, the energy was increased by 300% with a *utility factor* of $4.00/1.83 = 2.18$. The antenna configurations for this experiment were by no means unique, and it is possible to design many other patterns with similar results. A picture of the PCB set with four antennas is shown in Figure 11.

The above power results were available at four different terminals. For maximum energy harvesting, the individual dc power nodes were connected in parallel. The check on the power in the experiments was to vary the distance for the multiple-antenna sources to be compared against the single source. The results are shown in Figure 12, where the results for a single antenna acting as a single source are compared to the four antennas. With the outputs of the individual sources connected in parallel, the operational distance of the power device working at a voltage of 5 V was extended by 284%. This result is comparable with the 300% for the sum of the four antenna/device outputs when simply summed together. The results were considered to be within measurement tolerances.

Although there appears to be a saturation effect in Figure 12 as the distance decreased, this was an artifact of the test circuitry. To avoid touching the antennas in measuring voltage, a miniature A/D converter and infrared transmitter (see Figure 5) were used to wirelessly transmit voltage readings to an infrared receiver. To maintain a consistent precision in readings, the maximum dc voltage was chosen to be 5 V. Thus, the apparent saturation effect in Figure 12 was simply a saturation of the analog-to-digital converter, and not a saturation of the voltage.

5. Conclusion

In this paper, we have proposed the concept of locating multiple antennas in one space, which is not typically done as a means of increasing the energy or power/area ratio of an energy-harvesting device. The antenna design and measurement setup have been described in detail. A picture of the four-antenna configuration is given in Figure 11. The measurement results obtained suggest that this technique can be a very promising method. For the example chosen, an increase of 83% in area gave a 300% increase in available power to power a given load. One method of connecting the four sources was illustrated, which gave a 284% increase in the operational distance of the powered device. This concept is believed to be very useful in designs where a limited amount of space is available for the fabricating of energy-harvesting antennas.

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Introducing the Feature Article Authors

Minhong Mi received his BS in Electronics from Peking University in 1996, and his MS in Opto-Electronics from Shanghai Institute of Technical Physics, Chinese Academy of Sciences, in 1999. After receiving his PhD in Electrical Engineering from the University of Pittsburgh in 2003, he stayed at the same school as a postdoctoral research associate for one year to continue with his research in RF energy harvesting. He is currently an application engineer with Ansoft Corporation in Pittsburgh, supporting its high-frequency structure and circuit-simulation tools.

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Chris Capelli is currently the Director of the Office of Technology Management (OTM) for the University of Pittsburgh. There he directs the full scope of intellectual property management and technology licensing activities at the University of Pittsburgh ($515 million sponsored research expenditures). Since being named the director in 2001, Dr. Capelli has been directly involved with the negotiation, structuring, and completion of over 150 national and international licensing deals for the University, in both life science and non-life-science areas. During this period, Dr. Capelli participated in over of 30 startup ventures (five as a founder), spun-off from technologies invented and developed at the University.

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