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FAR-FIELD WIRELESS ENERGY HARVESTING FOR INCREASED SAFEGUARDS EQUIPMENT BATTERY LIFE

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1 Introduction

Modern unattended safeguards equipment (e.g. seals) incorporates many low-power electronic circuits, which are typically powered by expensive and toxic lithium thionyl chloride ($LiSOCL_2$) batteries. The limited life of these batteries necessitates their periodic replacement. This replacement must be performed before total battery discharge to avoid potential loss of continuity of knowledge. Thus, the effective battery capacity becomes significantly less than the actual usable capacity. Additionally, such maintenance is a radiological hazard to personnel, as well as a monetary burden to a safeguards inspectorate.

Energy harvesting, a commercially available technology, could extend the operational life of battery-powered equipment to achieve significant efficiencies for safeguards deployments. Energy harvesting is the scavenging and storage of ambient energy sources, such as solar, thermal, and kinetic for use in low-power electronic applications. While the amount of scavenged energy per unit time may be small, it most often comes from a source that will not be depleted throughout the deployment of the harvesting device. The best-known energy harvesters are solar panels and wind turbines.

Recently, far-field wireless energy harvesting has become a commercially available option. Far-field wireless energy harvesting provides consistent, predictable, and un-tethered power over distances up to 50 feet. This process converts radio frequency (RF) energy, both intentionally emitted and ambient, into usable direct current (DC) power. Incorporating far-field wireless energy harvesting into safeguards equipment can significantly extend the equipment's battery life and perhaps make it indefinite. Furthermore, additional functionality can be added to safeguards equipment without lowering its operational life expectancy.

This paper explores the benefits and drawbacks of integrating far-field wireless energy harvesting into a chosen safeguards seal: the Remotely Monitored Sealing Array (RMSA). Specifically, it examines the performance of a commercially available RF harvesting system from Powercast, as well as commercial and custom antenna solutions.

2 Far-field Wireless Energy Harvesting Overview

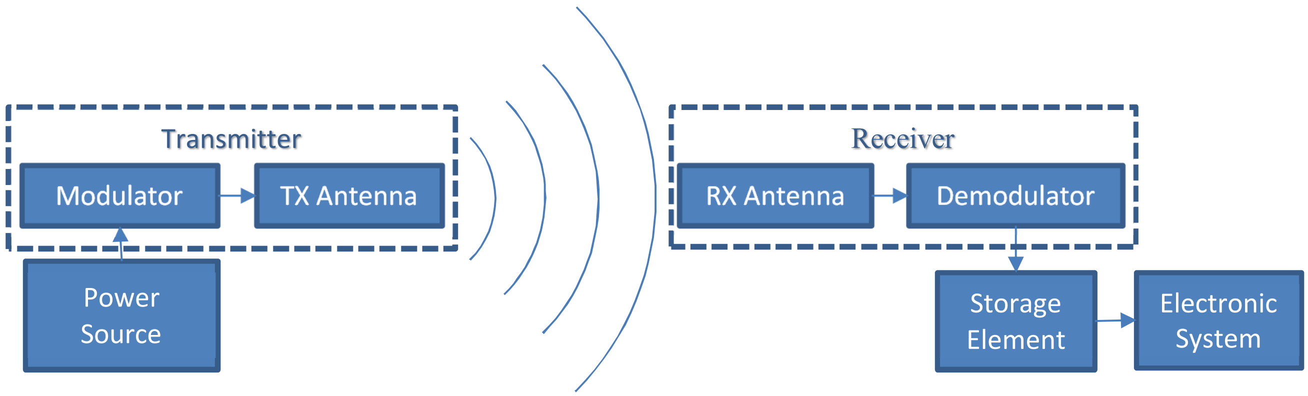


Figure 1. Wireless Energy Harvesting System

Figure 1 shows a high-level diagram of a wireless energy harvesting system.

While ambient RF energy is harvestable, its quantity is far from that required to supplement the power needs of an electronic system, even an extremely low-power one such as RMSA. Thus, a dedicated source of intentionally emitted RF energy must be present. This source of RF energy, known as a transmitter, is represented on the left side of Figure 1. Because it is intentionally emitted, the transmitter requires a source of facility power, such as 120/240 volt (V) wall power. This raw power is fed into a modulator, which transforms it into a modulated frequency and voltage that is easily and legally transmissible into free space. The modulator is then coupled into an antenna that converts the input electrical power into radio waves. The antenna can also polarize and beamform the radio waves to concentrate its output power into a specific region of space.

As the radio waves propagate through free space, they will eventually reach the receiver depicted on the right side of Figure 1. The electromagnetic energy of a radio wave spreads out as it propagates through free space (decreasing proportional to distance squared). Thus, it is imperative that the receiving unit be placed sufficiently close to the transmitting unit in order to maximize energy transfer. Reception occurs in the inverse of transmission. A receiving antenna converts the impinging radio waves into an output electrical power at the same modulated frequency. This electrical power is then fed into a demodulator, which demodulates the signal and rectifies it into a form of DC power. Finally, a storage element collects this DC power and makes it available to an end electronic system, such as an RMSA.

2.1 Transmitter

While a custom solution for the modulator and transmit (TX) antenna could be developed, a commercial option already exists: the Powercast TX91501, shown in Figure 2.

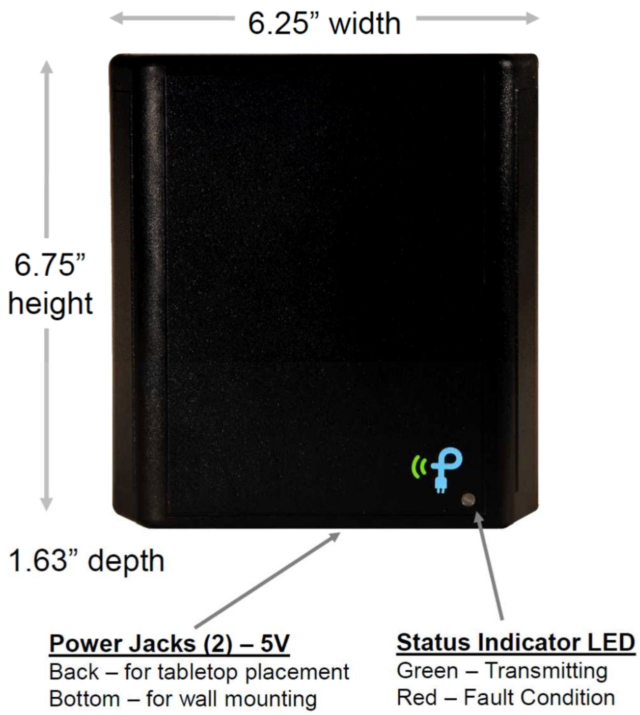


Figure 2. Powercast TX91501 Transmitter

Table 1 shows the specifications for the TX91501 transmitter. For the purposes of this research, only the 3 watt (W) transmitter was tested.

Table 1. TX91501 Specifications

Center Frequency	915 MHz
Modulation	Direct Sequence Spread Spectrum
Equivalent Isotropic Radiated Power	1 W or 3 W
Beam Pattern	60° width, 60° height, linear polarization
Power	+5 V_{DC}/1 A
Unit Cost (quantity 10)	$117 (1 W)/$206 (3 W)

The TX91501 is a plug-and-play solution, however design improvements in several areas would enhance its effectiveness. First, the TX91501 does not take full advantage of the Federal Communications Commission (FCC) limits. Part 15 of the FCC rules allows for an equivalent isotropic radiated power (EIRP) of 4 W, 33% higher than Powercast’s highest available power option. Increasing the power emitted by the unit will directly increase the power harvested at the receiver. Second, the TX antenna embedded in the TX91501 imparts a linear polarization to the output RF waves. This polarization creates an alignment issue with the receiver. If the receive (RX) antenna is also linearly polarized, the end user must align the transmitter and receiver along the same rotational axis. A misalignment of 45° will degrade the signal by up to +3 decibels (dBm), while a misalignment of 90° will attenuate the signal by +20 dBm, or more. Ideally, the transmitter and receiver would both use circularly polarized antennae, which only require that the antennae be polarized along the same axis of rotation, either right hand or left hand. No end user alignment is then required. Third, the transmitter uses a spread-spectrum modulation, while a better modulation choice would be single-tone continuous wave. Single-tone transmission would narrow the bandwidth of the system, resulting in a better input match and higher gain. It is also easier to tune the system for optimal performance at a single frequency rather than the various frequencies present in a spread spectrum system.

2.2 Demodulator

Like the transmitter, two demodulator options are commercially available from Powercast: the P1110 and the P2110B. Both are designed to operate in the 902-928 MHz frequency band and for standard 50 ohm (Ω) antennae. The P1110 is designed for short-range, continuously powered applications, while the P2110B is designed for long-range pulsed powered applications. Table 2 displays the complete specifications for both parts.

Table 2. Demodulator Specifications

	P1110	P2110B
RF Range	-5.0 dBm to +20 dBm	-12 dBm to +10 dBm
Output Voltage	Configurable: +1.8 V to +4.2 V	Configurable: +2 V to +5.5 V
Output Mode	Continuous DC	Regulated PWM
Unit Cost (quantity 10)	$31.50	$35.25

In operation, the P1110 will produce a charging current proportional to the input RF power. This charging current must be directed to a storage element placed in parallel with the connected electronic load. Once the voltage across the storage element reaches an adjustable threshold, the device disables charging. However, if the discharge rate of the load is greater than the charging current provided by the P1110, the output voltage will sag until an equilibrium is reached. In other words, as the transmitter moves further away from the receiver, it will eventually reach a point where the charging current is no longer sufficient to maintain a minimum operating voltage, and the harvesting capability will drop to zero. This behavior creates a hard limit on the allowable distance between which the transmitter and receiver.

The P2110B, on the other hand, does not provide a continuous output charging current. Instead, it deposits harvested RF energy on a local storage element not connected to the output electronic load. Once the energy stored passes a certain threshold, the P2110B boosts the voltage on the storage element to a configurable, regulated level and connects it to the load. It continues to supply this voltage to the load until the charge on the storage element decreases to a point where regulation is no longer possible. Then, the output voltage is disconnected and turned off. The result is a regulated pulse-width modulated (PWM) voltage output whose duty-cycle is proportional to the amount of energy being harvested.

Both devices provide a received signal strength indicator (RSSI), an analog voltage output that is proportional to the quantity of wireless energy being harvested.

2.3 Storage Element

Most electronic systems, especially ones containing microcontrollers and RF transceivers (such as the RMSA), present a widely varying dynamic load to the power delivery system. Ultra-low power sleep modes draw only nanoamperes of current, while data being transmitted across a wireless network can consume tens of milliamps. As such, some form of energy storage must be present in the energy harvesting architecture. This storage acts as a power buffer, storing harvested energy during periods of low demand and releasing it during peak demand to provide the power bursts necessary for operation.

Many different types of storage elements exist, generally in the form of either capacitors or batteries. While a virtually unlimited number of capacitor and battery options are available, only a select few meet the requirements for use in an energy harvesting application. First, the storage element must have an extremely low leakage current, ideally less than 1 microampere (µA). As leakage current increases, more harvested charge will be diverted to replace this lost capacity rather than refilling the storage element. Second, the storage element must be sufficiently large. If the storage element was to fill and to remain at capacity, any additional harvested charge would be lost. A general guideline would be to size the storage element capacity to be close to the maximum amount of charge required for the costliest operation in the system. For example, in the RMSA, the costliest operation is the generation, storage, and wireless transmission of a message. This operation requires an average current of 7 milliamperes (mA) for 220 milliseconds, approximately 1500 microcoulombs (µC). However, because other operations, such as checking the fiber loop, are occurring in the interleaving times, the energy harvester is unlikely to ever completely fill the storage element, and a smaller capacity may be chosen. Table 3 lists several options for storage elements.

Table 3. Storage Element Selection Criteria

System Requirement \ Storage Type	Ceramic Capacitor[1]	Aluminum Capacitor[2]	Electric Double Layer Capacitor[3]	Thin Film Battery[4]
Physical Size	20 mm^3	250 mm^3	1000 mm^3	250 mm^3
Unit Cost (quantity 10)	\$1.35	\$0.80	\$8.60	\$33
Availability	Excellent	Poor	Excellent	Poor
Leakage	1 µA	6 µA	5 µA	1%/year
Storage Capacity	725 µC	1500 µC	165,000 µC	2.5 C

Clear inability to meet requirement | Difficult to meet requirement | Clear advantage

[1] Samsung CL http://www.samsungsem.com/kr/support/product-search/mlcc/CL32A227MQVNNNE.jsp
[2] Vishay 013 RLC http://www.vishay.com/docs/28313/013rlc.pdf
[3] AVX BestCap http://datasheets.avx.com/BestCap.pdf
[4] STM EnFilm http://www.st.com/web/en/resource/technical/document/datasheet/CD00270103.pdf

2.4 RX Antenna

The most important component in the harvesting architecture is the receive antenna. Two key parameters for this antenna are the gain and the radiation pattern. The gain specifies the efficiency at which the antenna converts incident electromagnetic waves into electrical power. The radiation pattern defines the variation of receive energy as a function of direction and angle. Like the storage element, many options are available for this antenna, but few are actually feasible.

Figure 3. ANT-916-CW Dipole Antenna

Typically, wireless electronic systems use omnidirectional (360° energy pattern) antennae for communication, which are excellent for scavenging ambient, unintentionally emitted RF energy. An example would be the common half-wave dipole antenna from Linx, shown in Figure 3. However, these antennae are highly inefficient when used in a directed application such as energy harvesting, where RF energy is intentionally emitted from a known point source. A better option would be a directional patch antenna, which narrows the radiation pattern in exchange for a much higher gain. Powercast offers one such antenna, the PA-915-01, shown in Figure 4. This antenna's performance is maximized when directly facing the transmitter, offering 3.24x the gain of a standard dipole antenna.

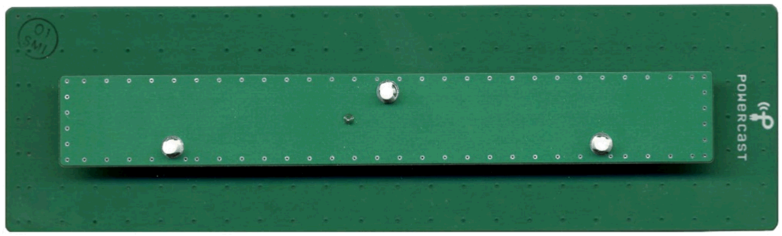


Figure 4. Powercast PA-915-01

While this antenna vastly outperforms a standard dipole antenna, the gain, and by extension, the harvesting efficiency-can further be improved by increasing the antenna's aperture. Figure 5 shows such a custom antenna, designed by SNL, with eight inch ruler for scale. This U-slot antenna has 6.31x the gain of the standard dipole antenna. Such an increase in gain will significantly extend the range of the system. Alternately, the power harvested at a fixed distance will increase dramatically.

Further performance improvements of the antenna can be realized by constructing an array. An antenna array connects individual antenna elements in a way that constructively combines the individual signals from each element to attain improved performance (when compared to the performance of a single element). The number of elements in the array can be anywhere from two to several thousand. The gain of the antenna generally doubles for each doubling of the number of antenna elements, so long as the underlying ground plane is sufficiently large. However, the size, weight, and cost of the antenna also increase dramatically. Figure 6 is an example of a SNL-designed 2 element by 2 element antenna array, while Table 4 lists the complete specifications of all three antennae. Note that while the performance of the 2x2 array is markedly better, its large size and weight make its mounting and usage borderline infeasible atop a seal such as RMSA as most antenna connectors available would not be able to mechanically support such a structure without deforming.

Figure 5. SNL-designed U-Slot Antenna

Figure 6. SNL-designed 2x2 Antenna Array

	PA-915-01	SNL U-Slot	SNL 2x2 Array
Gain (dBi)	6.1	8.9	13.9
Bandwidth (2:1 VSWR)	22 MHz	129 MHz	160 MHz
Radiation Pattern	122° x 68°	67° x 71°	38° x 38°
Size	7” x 2”	9” Ø	11.4” x 11.4”
Weight (grams)	48	206	540
Unit Cost (quantity 10)	$39.95	$32.15	$50.29

Table 4. Antennae Specifications

3 Seal Integration

To incorporate energy harvesting capability with a safeguards seal such as RMSA, several mechanical and electrical design considerations must be taken into account. First, the energy harvesting demodulator must be electrically connected to the base seal hardware. One approach would be to directly integrate the harvesting electronics into the base seal printed circuit board. While this solution is the simplest mechanically, it demodularizes the design. Should the seal user want to use a different harvester, the entire base board must be re-fabricated. An alternative approach is to place the harvester on a daughter card that is then plugged or cabled into the base electronics. This way the harvester electronics can be modified or replaced without having to alter the base seal hardware. For integration with RMSA, I chose this approach. Figure 7 presents the modularized harvester, displaying daughter cards for both the P1110 and the P2110B.

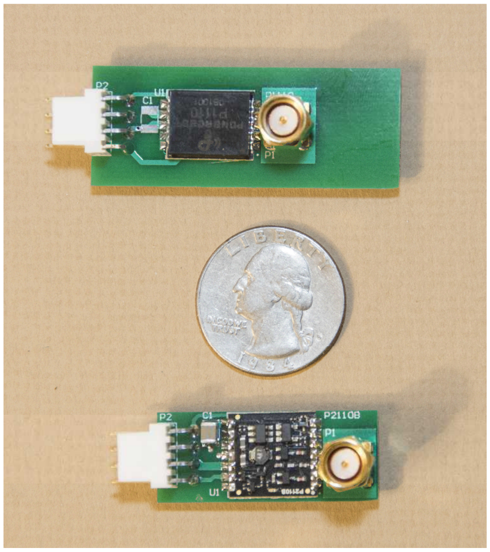


Figure 7. Harvesting Daughter Cards

Next, the RX antenna must be mounted and electrically connected to the seal. It is tempting to want to use the same antenna for both harvesting and communication. However, due to the directional nature of the harvesting antenna, a two-antenna design is necessary. For RMSA, the normal internal F-antenna is used for all wireless communications, while the energy harvesting antenna is mounted externally. This configuration has the added benefit of reusing the existing RMSA cases. No additional tooling is necessary, as RMSA housings configured for an external antenna already exist.

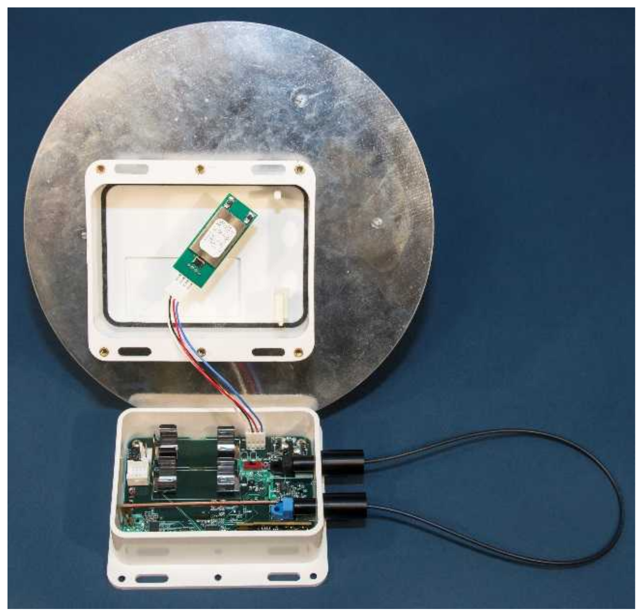


Figure 8. Fully Assembled Unit with Lid Open

Figure 8 shows the fully assembled RMSA with lid open, showing the attached harvesting daughter card and external U-Slot antenna. The internal copper F-antenna can be seen at the bottom of the base enclosure. Batteries are still contained in the unit; the holders are located directly above the F-antenna. Regardless of the amount of energy harvestable, batteries are always needed in the system. Without them, an adversary could unplug the transmitter or unscrew the RX antenna to force the seal to power down. Nevertheless, the harvesting capability allows for smaller, cheaper batteries with lower toxicity.

Lastly, the RMSA firmware must be slightly modified. In order to provide a seal inspectorate with feedback on harvesting performance, the seal microcontroller monitors the analog RSSI output from the harvester, digitizes it, and reports the information in the periodic state-of-health message. This information is also useful during seal installation, as an inspector can modify the seal's position and angle and receive real-time feedback on the subsequent performance changes.

4 Performance

Two suites of testing measured the performance of the harvesting systems. In the first, I connected the P1110 to a static load of 100 kΩ in parallel with an AVX supercapacitor while setting the output voltage of the harvester to +3.3 V. The total load, including leakage, was ~40 µA, approximately double that of an RMSA at room temperature. In the second part of the test, I placed the harvester in direct line of sight of the transmitter. I then moved the receiver away incrementally until the output load voltage just began to drop. This distance is the breakeven point between energy being harvested and energy being consumed by the load. I then repeated the second part of this same test, but with the receiver moved laterally and closer to the transmitter. By plotting several distances vertically and horizontally, I generated a range map for each antenna type, shown in Figure 9. This map plots the theoretical area in which an end-user could place the receiver relative to the transmitter and be able to fully power the static load. Note that the receiver and transmitter must be aligned parallel to each other and that the antenna polarizations must match. Additionally, multipath interference may cause dropouts within this area, where the received signal strength is different than it would be in a reflection-free facility.

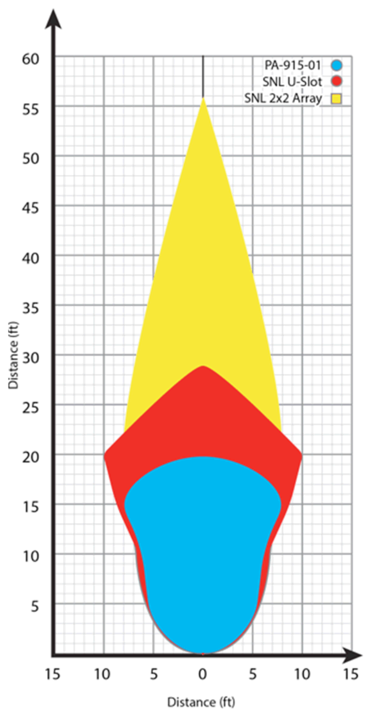
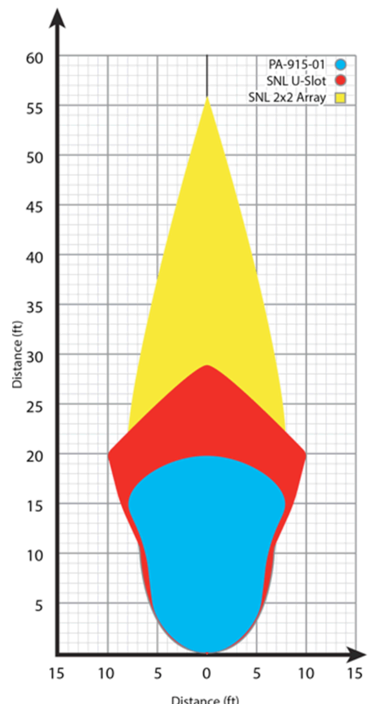


Figure 9. P1110 Range Map



For the second test, I configured the unit in Figure 8 for normal seal operation and placed it directly in line of sight of the transmitter. However, instead of using batteries to power the system, I employed a very large (> 5 Farads) bank of supercapacitors charged to +3.3 V. For each test, I ran the system for at least four hours while recording the voltage drop across the capacitor bank. By measuring the starting and ending voltages of the test, as well the exact test time and capacitance value, one can calculate the average current draw of the system as follows: $I = \frac{C(V_1 - V_2)}{t}$. The energy provided from the harvesting circuit can then be calculated by differencing the baseline current draw with no harvesting capability from the current draw with harvester attached. Note that the leakage current of the capacitors must be accounted for in these tests, as it can comprise > 75% of the charge loss.

For this test, I configured the combined unit separately with both the P1110 and the P2110B, and tested each with the transmitter placed in a straight line with the receiver (no lateral displacement). I repeated the test while varying the separation between the transmitter and receiver in fixed increments. I used the U-Slot antenna for all tests. Figure 10 shows the results.

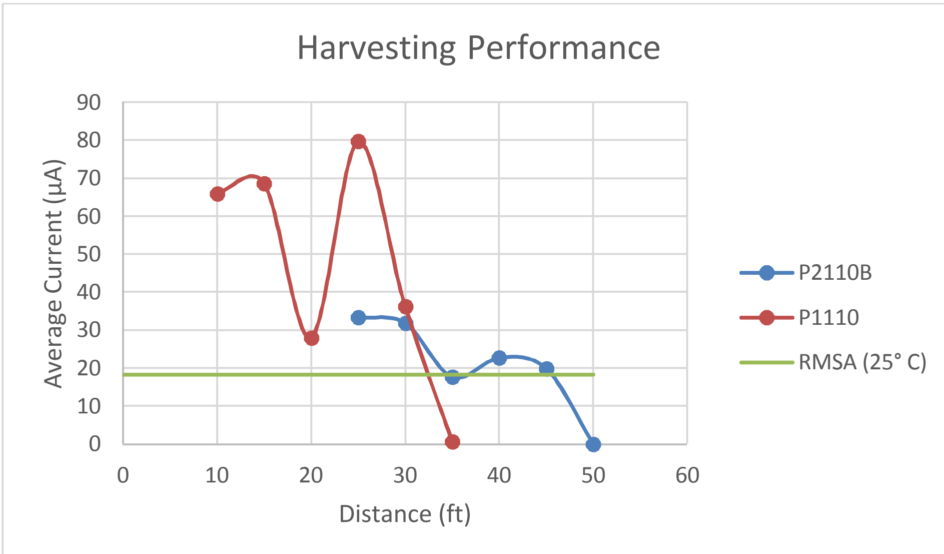


Figure 10. Harvesting Results

The green line represents the baseline current draw of an RMSA. For distances of 30 feet or less, the P1110 provides double to triple the current needed for an RMSA to run. Note the room-dependent multipath interference causing destructive interference at 20 feet and constructive interference at 25 feet. For longer range requirements, the P2110B can fully power an RMSA at a distance of 45 feet.

5 Enhancements

5.1 Transmitter

As mentioned in section 2.1, design improvements to the transmitter would enhance its efficacy significantly. The output of the TX91501 transmitter is 1 W below the regulatory limit (4 W or +36 dBm), while also being inefficiently spread out over a larger than necessary bandwidth. A new transmitter circuit design fixes both issues. The finished circuit is shown in Figure 11.

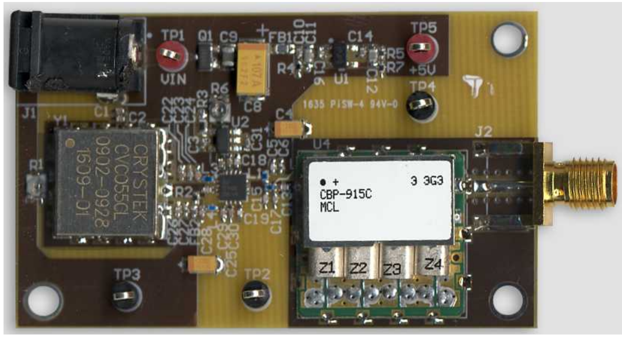


Figure 11. Custom Transmitter Circuit

The design is conceptually simple, with a total parts cost of less than $100. Figure 12 depicts a block diagram of the circuit. Unregulated +5 V power is supplied via the same power source and connector type as the original TX91501. This power is regulated by the board and then fed to a voltage controlled oscillator (OSC). This oscillator outputs a sine wave between 902 and 928 MHz and contains a tuning port (V_{TUNE}) to allow precise calibration and temperature compensation of the output. However, by itself, the oscillator provides only +5 dBm of power. An RF power amplifier (PA) boosts this weak signal into a far stronger signal capable of driving an antenna and producing the required +36 dBm of power. Like the oscillator, this amplifier is in-system configurable; its output power is tunable over a wide range (-10 dBm to +35 dBm) using the automatic power control (V_{APC}) port. However, once tuned to the appropriate power, and before driving the antenna, any spectral components of the amplifier outside the allowed spectral band must be suppressed to comply with regulator limits. A bandpass filter (BPF) accomplishes this suppression, and its output is fed directly into the antenna which provides the final gain required to reach the desired power level.

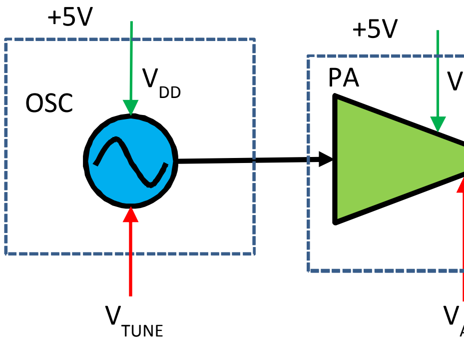


Figure 12. Custom Transmitter Block Diagram

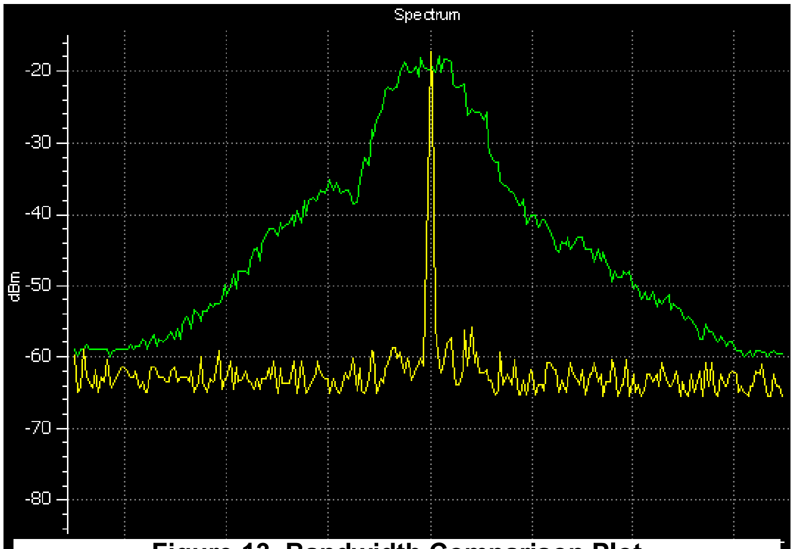


Figure 13. Bandwidth Comparison Plot

Figure 13 displays a bandwidth comparison between the two transmitters captured on a spectrum analyzer. The TX91501 output is in green, while the custom transmitter is in yellow. While the absolute bandwidth of both circuits is not directly measurable from this plot, as both exceed the maximum resolution of the analyzer and are clipped, the relative difference in bandwidth is obvious. The custom transmitter forms a tight peak centered around 915 MHz, while the TX91501 is spread across many MHz. In addition to having a better match with the antenna and receiver, this narrowing of the bandwidth also prevents the transmitter from jamming other RF devices in the area trying to use nearby frequency channels.

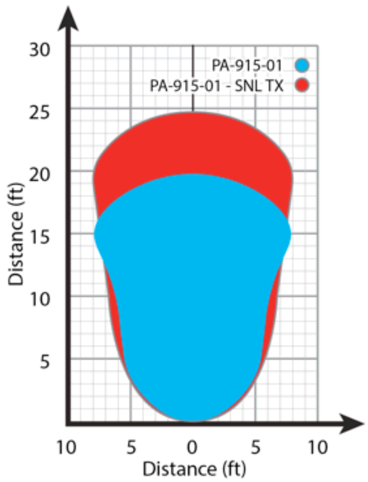


Figure 14. Transmitter Power Comparison

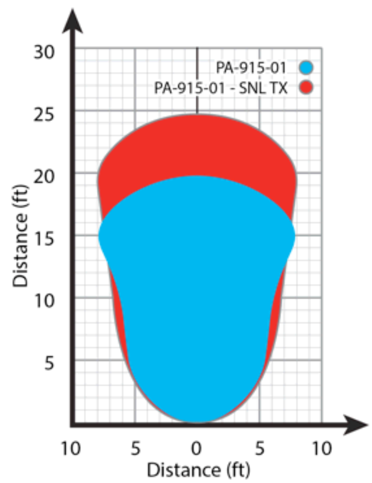


Figure 14 shows the increase in P1110 operational range resulting from increasing the transmitter's output power from 3 W to 4 W. The configuration for this test was the PA-915-01 antenna connected to the receiver and the U-slot antenna connected to the custom transmitter. As expected, the custom transmitter achieved close to a 33% increase in downfield range. The side to side range was unaffected, as it depends on the antenna's radiation pattern which was not changed.

5.2 Antenna

Another improvement mentioned in section 2.1 is a circularly polarized antenna for both the transmitter and receiver. All antennae evaluated thus far have been linearly polarized. Linearly polarized antennas broadcast their energy in a single plane, either horizontal or vertical. They are compact in size but require careful orientation and must be aligned along identical planes. As previously discussed, misalignment of these antennae will reduce the received signal strength, upwards of +20 dBm if cross polarized. Circularly polarized antennae mitigate this concern by broadcasting their energy across both horizontal and vertical planes in a corkscrew pattern. So long as both antennae use the same axis of rotation, no cross polarization can occur no matter the angle of rotation between antennae. This degree of freedom does not come for free, however, as the antenna must now spread its output energy across both planes. For a given size, a circularly polarized antenna will have +3 dBM (50%) less gain than a similarly sized linearly polarized antenna. To compensate for this loss of gain, the circularly polarized antenna must be made larger.

Figure 15 displays a SNL-designed circularly polarized antenna with 8 inch ruler for scale.

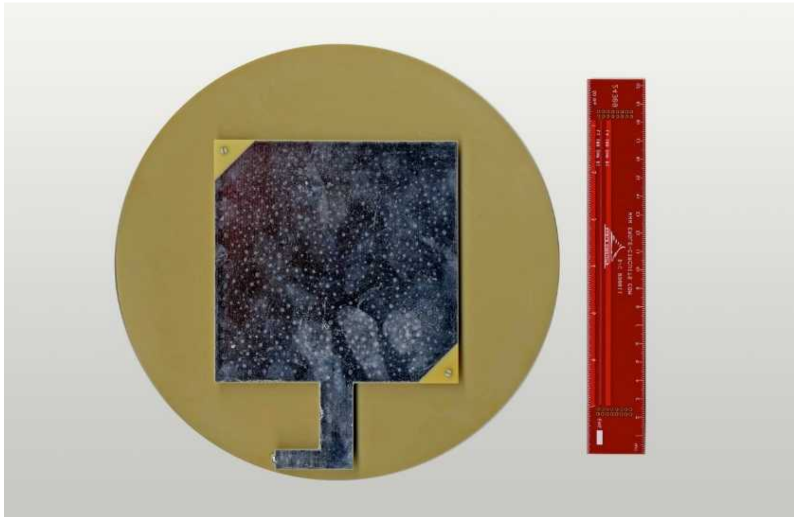


Figure 15. SNL-designed Circularly Polarized Antenna

This antenna is very similar in construction to the custom U-Slot antenna shown in Figure 5. However, to compensate for the loss in gain, the circular ground plane had to be enlarged. A full comparison of both antennae is given in Table 5.

Table 5. Antennae comparison

	Custom U-Slot	Custom Circularly Polarized
Gain (dBi)	8.9	8.1
Bandwidth (2:1 VSWR)	129 MHz	55 MHz
Radiation Pattern	67° x 71°	60° x 60°
Size	9” Ø	10” Ø
Weight (grams)	206	218
Unit Cost (quantity 10)	$32.15	$34.36

6 Conclusions

Far-field wireless energy harvesting is a serviceable technology to extend the operational lifetime of battery-powered safeguards equipment. It can provide 100% of the power needs of an RMSA at distances of up to 45 feet for less than $100 (excluding transmitter). It also allows for the replacement of $LiSOCL_2$ batteries with traditional lithium ion batteries, a far less toxic and far more environmentally friendly substitute. However, non-trivial barriers to adoption exist. This technology requires careful positioning and alignment of both the transmitter and receiver. Both units must face each other, have line of sight, and not exceed 60° of horizontal displacement. Linear polarized antennae require further alignment, removing an additional degree of freedom from the system setup. Nevertheless, once the system is established, the technology can achieve self-sustainable operability for safeguards equipment.

7 Acknowledgements

The author gratefully acknowledges funding support from the US Department of Energy/National Nuclear Security Administration Safeguards Technology Development Team (NA-241).