Power-Optimized Waveforms for Improving the Range and Reliability of RFID Systems

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***Abstract*—A major limitation in passive radio frequency identification (RFID) is the read range from the reader to tag, which is limited by the power available to the radio frequency integrated circuit (RFIC). The power-optimized waveform (POW) is a new type of multiple-tone carrier and modulation scheme that is designed to improve the read range and power efficiency of charge pump-based passive RFICs. This paper presents the POW concept, an estimation of effects on existing class 1 generation 2 RFID systems, several example POWs, simulation results, and measurement results of read range gains using a POW.**

I. Introduction

Read ranges of passive ultra-high frequency (UHF) RFID tags are limited by the RFIC's ability to power itself by rectifying a reader's continuous-wave (CW) carrier. In this paper, we demonstrate a new technique for providing a potential order-of-magnitude increase in read range by employing a Power-Optimized Waveform (POW) at an RFID reader. A POW-based RFID reader enhances read range of a passive RFID tag by shaping the RF carrier envelope in a way that exploits the nonlinear behavior of the tag's on board semiconductor charge pumps. We demonstrate how the shaped POW signal from the reader can power up RF tags over much larger distances without exceeding the average equivalent isotropically radiated power (EIRP) transmit power or the FCC-allotted industrial, scientific, and medical (ISM) bandwidth. Such a range enhancement would enable countless new applications for passive RFID technology as well as for energy-harvesting devices such as sensors, personal area data devices, and other low-powered consumer electronics.

In a conventional RFID system, the reader sends continuous wave (CW) energy to the tag, and the tag rectifies this energy to power the tag's RFIC. The RFIC then modulates the incoming CW wave and backscatters the energy to the reader. Common applications of backscatter radio include supply chain management, toll collection, baggage handling, passive sensing, and passive data storage [1]. Passive tags have no local power source to use for transmitting or processing, and they require all power to come from the reader. Read range is the maximum distance a reader can be placed away from a tag in order to reliably receive the backscattered information. The maximum read range for passive RF tags at UHF frequencies is typically 2 to 10 m [2].

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This research was sponsered by NSF CMDITR grant #0120967.

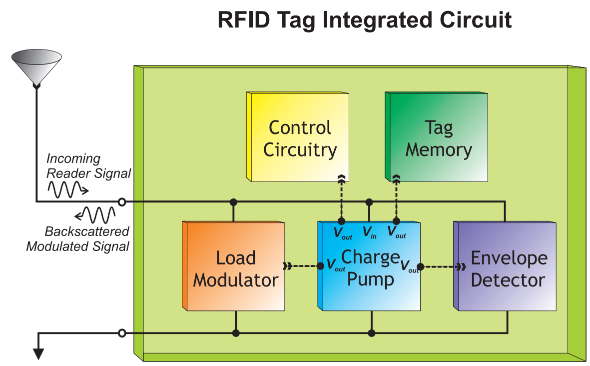

Fig. 1. Block diagram of a passive RF tag showing how the charge pump provides power for the tag's control circuitry, load modulator, tag memory, and envelope detector.

Passive RF tags use rectifying charge pump circuits to convert the CW power into DC power for the RFIC. Figure 1 shows a basic block diagram of a passive RF tag. The charge pump provides power to all tag blocks including the load modulator, control circuitry, tag memory, and envelope detector. Common charge pump circuits such as the voltage doubler, the voltage quadrupler, and the N-stage charge pump are used in passive tags and are shown in Figure 2. A passive tag's read range is limited by the poor power efficiency of its rectifying charge pump circuits, which have typical power efficiencies in the range of 15% to 80% [2]. Read range can be increased by increasing the power efficiency of these circuits.

This paper presents the POW, which is a new, multiple-tone carrier and modulation scheme that can improve the range and reliability of passive RF tags by increasing charge pump power efficiency. The POW increases charge pump efficiency by providing larger peak voltages to the tag while maintaining the same average conducted power as the standard 915 MHz reader waveform. The POW mixes with the baseband transmitter signal in both the transmitter and receiver sections of the reader for both forward and backward communications. The remainder of this paper explains the POW concept and

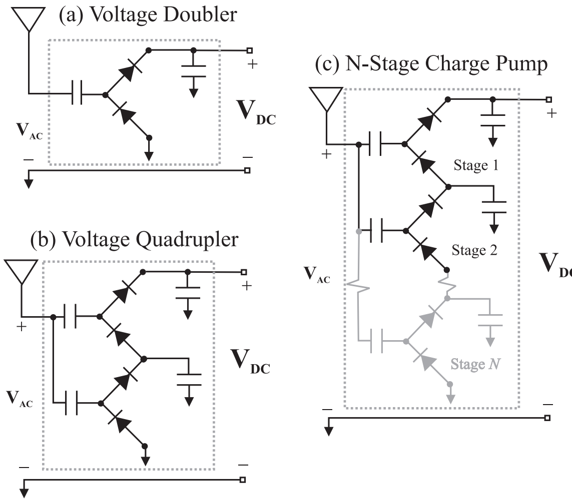

Fig. 2. Common charge pumps used in RFID tags such as the (a) voltage doubler, (b) voltage quadrupler, and (c) N-stage charge pump, which are based on the Dickson charge pump topology [3]

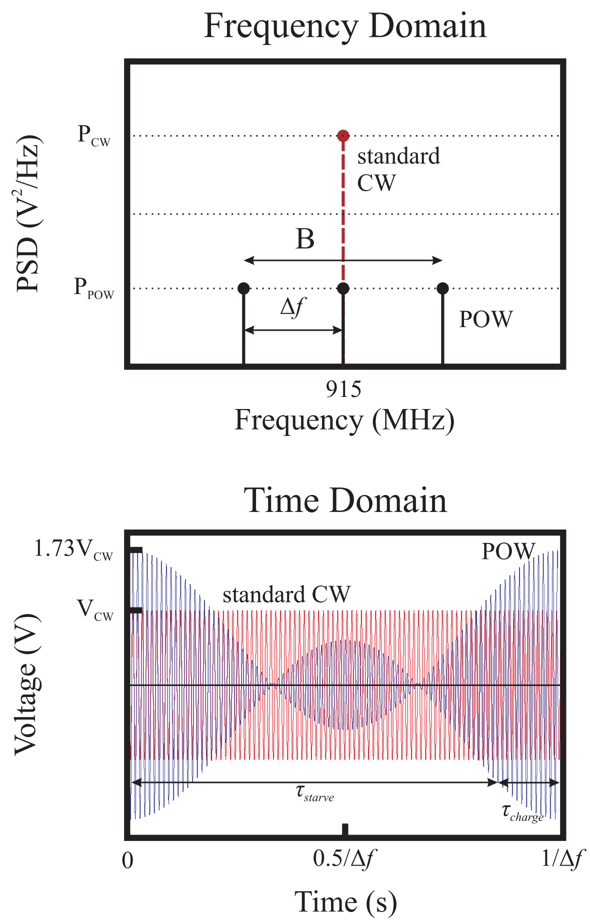

Fig. 3. Time- and frequency-domain plots of an example 3 subcarrier POW. The POW has a larger peak voltage and the same RMS voltage as the standard CW.

presents simulations of charge pump outputs with a POW input to demonstrate the efficiency gains with a few example POWs. Last, measurements of read range gains using a POW are presented showing the POW's effectiveness.

II. The POW Concept

A POW is a multiple-tone carrier that is designed to improve the power efficiency of charge pump-based RFID tags while preserving the ability to exchange information with the RF tag and reader. The envelope of the POW is specially designed to have large peaks, low valleys, and the same RMS voltage as the standard 915 MHz carrier currently used in readers. Therefore, the instantaneous peak voltage delivered to the tag charge pump is increased while still meeting FCC power regulations.

A time- and frequency-domain description of an example POW with three subcarriers is shown in Figure 3. The frequency-domain graph shows that the POW components are each at a third of the power of the standard CW, ensuring that the total power of the POW is the same as the standard CW wave. The time-domain representation of a general, simple POW with N subcarriers is a summation of N sine waves:

$$V_{\text{POW}}(t) = \sum_{k=0}^{N-1} \frac{1}{\sqrt{N}} \sin\left(2\pi(f_{\min} + k\Delta f)t\right) \tag{1}$$

The bandwidth occupied by a simple POW is $(N-1)\Delta f$. The lower bound on the bandwidth, B, is the minimum frequency, $f_{\min}$, and the maximum frequency is $f_{\min} + B$. The RMS voltage of Eqn. (1) is normalized to be identical to a unity amplitude CW, $1/\sqrt{2} \approx 0.707$. The simple POW's maximum voltage value is $\sqrt{N}$, which is larger than the standard CW amplitude of 1 and occurs when each subcarrier reaches a peak. The simple POW frequency is Δf and is the same as the beat frequency for a set of subcarriers, i.e. the lowest common multiple of the frequency differences between subcarriers. Thus, one POW period $(1/\Delta f)$ is longer than the standard CW time period (1/915 MHz = 1.09 ns). Increasing the number of subcarriers increases the peak voltage, but the trade off is increased bandwidth and/or increased time period between voltage peaks if Δf is reduced.

The large peaks of the POW produce better power efficiencies than a single CW for standard RFID power rectifying circuits. All of the standard charge pump rectifying circuits in Figure 2 use diode-connected capacitors to rectify the input voltage and pump charge from stage to stage to build a large DC output voltage. The diode is useful for controlling current flow, but it limits the voltage each capacitor absorbs during a cycle by V_t Volts, the diode threshold voltage. Charge pump power efficiency is adversely affected by increasing threshold voltage but is favorably affected by increasing input voltage. The large peaks of the POW provide a large input voltage and allow the tag to be placed farther away from the reader while maintaining its input power.

The limitations of this technique are more difficult envelope detection and larger occupied bandwidth. The POW's long time period may be a problem for envelope detection within a tag. Consider the typical envelope detector composed of

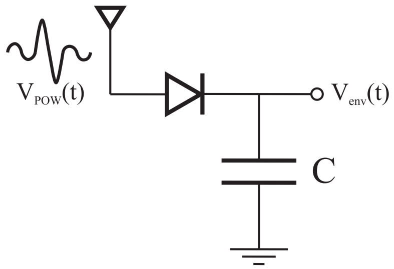

Fig. 4. Common envelope detector used in most class 1, generation 2 RFID tags. A POW's large maximum voltage allows more charge to flow into the capacitor than with the standard CW.

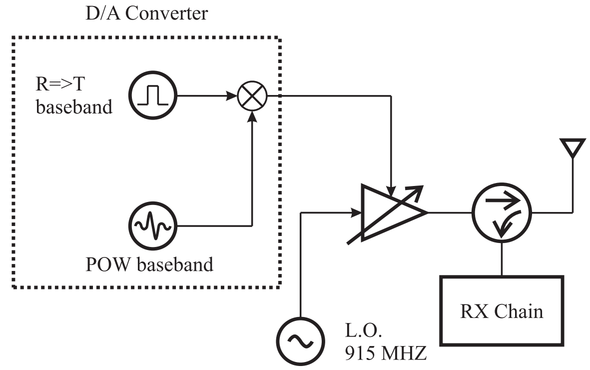

Fig. 6. Basic RFID reader system diagram modified to use a POW LO

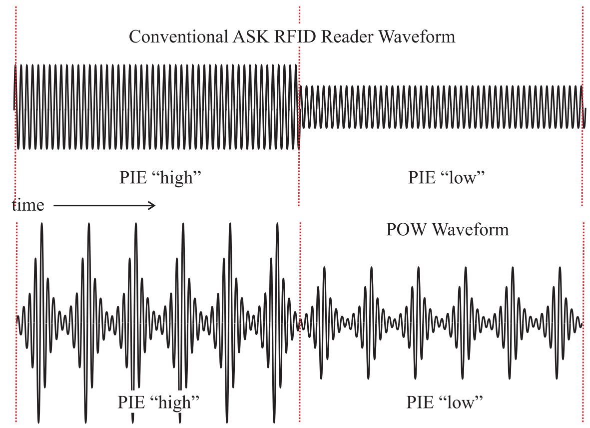

Fig. 7. Pulse Interval Encoding (PIE) ASK "high" and "low" using conventional CW (top) and POW (bottom).

a diode-connected capacitor with a large discharge time as shown in Figure 4. The capacitor charges up to the maximum input voltage, and then discharges until the next maximum occurs. The capacitance must be sufficiently large to enough to allow the envelope voltage to last between POW peaks. The bandwidth occupied by a POW is larger than a standard CW's bandwidth, which presents a problem for meeting spectral mask requirements, but it can be done using specially designed POWs as discussed in section V.

III. Simulations of 915 MHz Charge Pumps

Circuit simulations of the voltage doubler from Figure 2 with standard CW and simple multi-tone POW waveforms were run to compare output voltage, ripple voltage, efficiency, starve time, and charge time. The capacitors were set to 100 pF each, and the output was connected to a 100 kΩ resistor. The diodes are Silicon-based 1N4500 with a threshold voltage of $V_t = 0.7$. Table I shows the results for a CW input and three different POW inputs. The POW inputs follow the form shown in Figure 3 with $\Delta f = 2$ MHz spacing, which results in a period of 500 ns. Each subcarrier in the POW has power $1/N$, where N is the number of subcarriers. This ensures the RMS voltage of each input in the table has the same RMS voltage as the unity amplitude CW, $1/\sqrt{2}$.

Figure 5a shows the output voltage waveform of the voltage doubler with a standard 915 MHz CW input. Figures 5b through 5c show the voltage doubler output under the three different POW inputs. Figure 5b shows the output voltage of the voltage doubler for a simple 2 subcarrier POW input. The output voltage rose to 2.38 V, and the ripple voltage rose to 380 mV. Figure 5c shows the output voltage, V_O, of the voltage doubler for a simple 4 subcarrier POW input. The charge time is 59 ns while the starve time is 441 ns. Figure 5d shows the output for a simple 8 subcarrier POW input. The output voltage increased to 5.08 V, and the charge time decreased to 30 ns. The ripple voltage is larger at 927 mV. In all of the POW input cases, the voltage and power efficiency rose significantly over the standard CW case, as well as the ripple voltage.

Table I shows that the output voltage increased as the number of subcarriers increased, which is due to the fact that the maximum input voltage increased as well. The output voltage approached twice the input voltage as the number of subcarriers increased, likewise the power efficiency increased with the number of subcarriers. Ripple voltage increased with the number of subcarriers also due to a larger peak output. Notice that the charge time and starve time add up to the period of the input waveform for each POW input case. As the number of subcarriers increased, the starve time increased and charge time decreased indicating the capacitors absorbed increasingly larger current impulses.

IV. POW Implementation

The POW can be synthesized by mixing a POW signal envelope with an LO at 915 MHz to get the desired POW as shown in Figure 6. This procedure is performed within the reader and requires no changes within the tag. The POW envelope is constructed and mixed with reader-to-tag (R=>T) commands such as select, query, and acknowledge [4] within a D/A converter.

A. Forward Communications

Most reader configurations use a D/A in some fashion and have a 915 MHz LO on board, thus updating the code within the reader to produce a baseband POW is all that needs to be done to adapt the reader to a POW. Readers using pulsed interval encoding (PIE) will be able to modulate the POW as shown in Figure 7. Digital symbols 1 and 0 both use PIE "high" and "low" as part of their time domain waveforms,

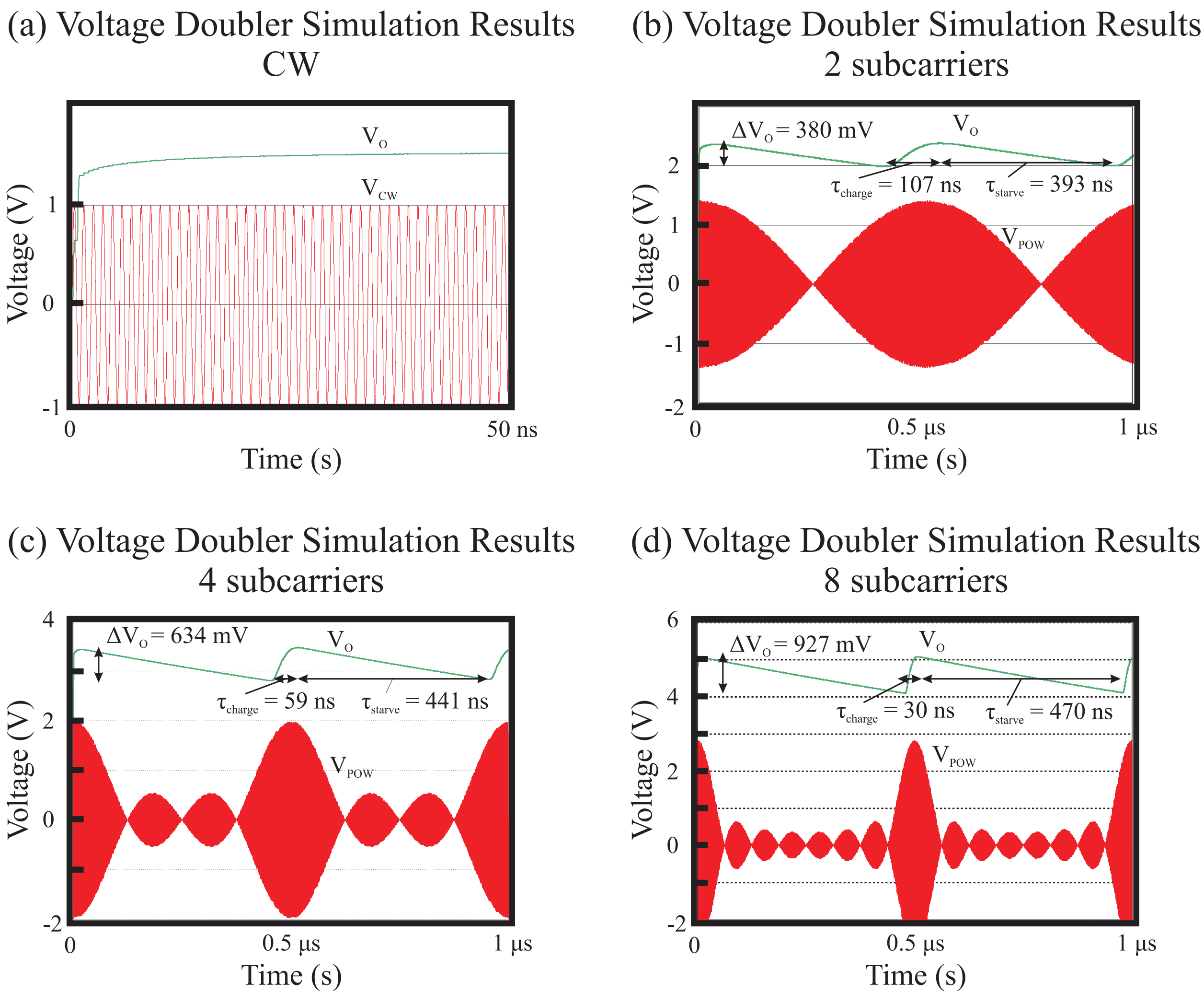

Fig. 5. Simulation results of voltage doubler with (a) standard 915 MHz CW input, (b) 2 subcarrier simple POW input, (c) 4 subcarrier simple POW input, and (d) 8 subcarrier simple POW input all with RMS voltage of $1/\sqrt{2}$. V_{POW} denotes the input POW, V_{CW} denotes the input CW, V_{O} denotes the output voltage waveform, ΔV_{O} denotes output ripple voltage, τ_{charge} denotes charge time, and τ_{starve} denotes starve time.

TABLE I
VOLTAGE DOUBLER SIMULATION RESULTS

Input Type	Output Voltage	Output Ripple	Power Efficiency	Starve Time	Charge Time
915 MHz CW	1.53 V	1.25 mV	76.5 %	0.46 ns	0.08 ns
2-subcarrier POW	2.38 V	380 mV	84.1 %	107 ns	393 ns
4-subcarrier POW	3.47 V	634 mV	86.8 %	441 ns	59 ns
8-subcarrier POW	5.08 V	927 mV	89.8 %	470 ns	30 ns

and the POW can be designed with a short time period to fit multiple peaks under a “high” or “low”.

The passive RF tag does not need to be altered to implement the POW so long as the ripple capacitors in the envelope detector and charge pump circuits are large enough to limit the ripple voltage to a reasonable level. A POW will have a longer time period between peaks than the standard CW, and the ripple capacitors must be increased by the ratio of POW period to CW period in order to maintain the same percent ripple as in the conventional CW case. However, the voltage regulator in the passive tag will likely absorb the extra ripple since the POW provides larger output voltages than the standard CW [5]. Altogether, this means that while no tag changes are needed, an increase in ripple capacitor size would help the tag’s power handling capability.

B. Backscatter Communications

The backscatter channel from the tag to the reader receiver using a POW experiences similar spatial fading as a backscatter channel using CW since the frequency content is in the

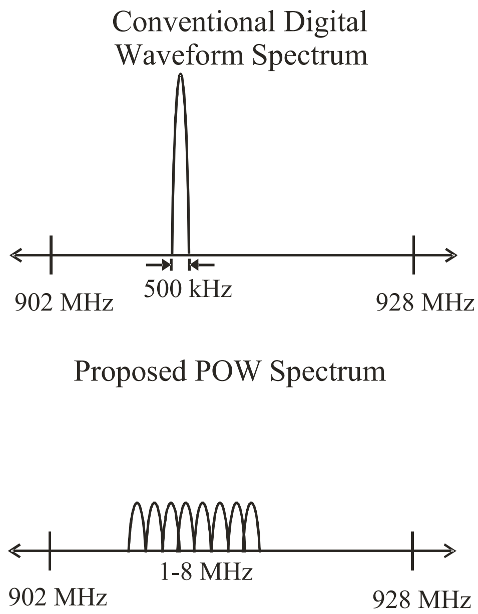

Fig. 8. Sketch of the spectrum of conventional digital (top) and proposed digital (bottom) signals, both of which maintain identical maximum conducted output power.

same 902 - 928 MHz industrial, scientific, and medical (ISM) band. No significant changes need to be made in the reader receiver. A matched filter with the same POW source from the D/A converter in Figure 6 will suffice for receiving the backscattered signal.

C. FCC Compliance

The POW technique can be designed to operate under the FCC Part 15 Rules, Section 247, which governs digitally modulated intentional radiators. A conventional RFID reader intentionally radiates a single-tone, digitally amplitude-modulated (AM) wave to power an RFID tag wirelessly. Section 15.247, paragraph (b) (3) states that the maximum conducted output power must be less than 1 Watt [6]. Thus, this POW method may not transmit more than 1 Watt of power averaged over the symbol alphabet, which is the length of time it takes to transmit all symbols in the alphabet. The symbol alphabet for the use of a POW is only two bits long (symbol one or symbol zero), and the average is equal to the RMS power of the waveform. The POW technique was designed to have large instantaneous peak power, however its RMS power is the same as the standard CW; Therefore, the POW technique will meet FCC rules in the same manner that the conventional single-tone method does.

The only limitation for the POW technique is restricting the POW spectrum to conform to a 500 kHz channel in multiple-interrogator mode as set by the FCC in the 902 - 928 MHz ISM band [6] and a 200 kHz channel as set by the European Telecommunications Standards Institute (ETSI) in the band, 865 - 868 MHz [7]. Figure 8 compares the spectrum of the standard CW signal to the proposed spectrum of the POW. The POW spectrum has less maximum power spectral density at any particular frequency because the power is spread across the frequency band. The POW spectrum can resemble a spread spectrum and/or OFDM-type digital signal, often making a more benevolent interferant than conventional frequency-hopping narrow band RFID readers. The total power is the same for both the CW and POW. According to the Part 15.247 rules, the spectral mask must not exceed “8 dBm in any 3 kHz band during any interval of transmission” [6]. Since the conventional amplitude shift keyed (ASK) waveform can be designed to meet this maximum power spectral density requirement, the proposed POW version of an RFID reader waveform will be significantly less than the maximum allowed power spectral density.

V. Example POWs

There are many forms of a POW. The defining characteristics of a POW are multiple tones, large peaks, and lengthy valleys. A POW must have the same average conducted power, or the same RMS voltage, as the standard CW wave for comparisons of power efficiency, read range, and reliability tests. How to match the optimal POW shape and number of subcarriers to the charge-pump hardware and RFIC architecture is an open research question. Three example POWs, the simple POW, the Gaussian POW, and the raised cosine POW, are shown, and the benefits and drawbacks of each are given.

A simple POW is constructed with N subcarriers at equal power normalized to a total power of one. An example with $N = 3$ was shown previously in Figure 3. This POW is beneficial because it is easy to implement in hardware and simple to code in software in a D/A configuration. The drawback is its poor spectral mask aspects, which represents a rectangle and does not decay from the center frequency. This spectrum may leak too much power into restricted frequency bands if it is not designed correctly. Meeting the spectral mask for specific applications such as RFID communications at 915 MHz can be accomplished if the peak power spectral density does not exceed the FCC mask requirements in the designed POW bandwidth.

A Gaussian POW is shown in Figure 9. In this example POW, 8 POW baseband subcarriers (0 MHz, 1 MHz, 2 MHz, . . ., 7 MHz) were conformed to a Gaussian PSD envelope, as shown. The baseband POW was mixed with a 100 MHz signal to produce the time-domain graph in the figure. This method can be employed in hardware with weightings for each frequency source to construct the baseband POW. With a D/A converter used to drive the transmitter, the code can specify the baseband Gaussian envelope in the frequency domain and then perform an inverse fast Fourier transform to get the time-domain baseband POW. The benefit of using the Gaussian POW is its excellent spectral mask - the power is concentrated near the center frequency and tapers off exponentially making it a good candidate for meeting most spectral mask requirements.

A raised cosine pulse POW is shown in Figure 10 and is another POW that has good spectral mask aspects. The

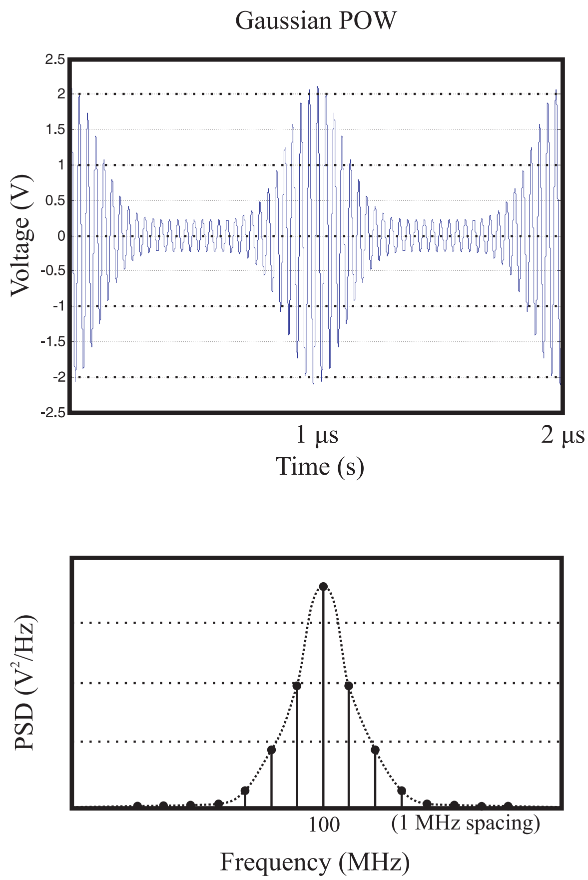

Fig. 9. Time- and frequency-domain depictions of a Gaussian POW using eight subcarriers separated by 1 MHz from 0 to 7 MHz and modulated with a 100 MHz LO for picture clarity.

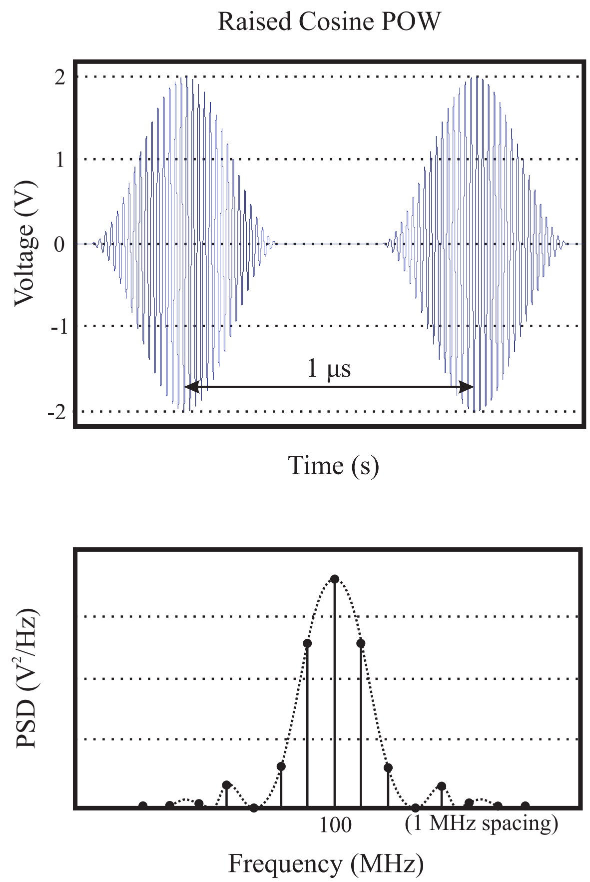

Fig. 10. Time- and frequency-domain depictions of a raised cosine POW created in a D/A converter environment modulated with a 100 MHz LO for clarity.

waveform was created with raised cosines of amplitude 2 V and width 0.667 μs separated by 1 μs in the time domain. The spectrum looks like a repetitive sinc-type pulse with roll-off factor of 1 modulated at the carrier frequency. This spectrum can be bandpass filtered beyond the first nulls and still retain the same basic shape as in Figure 10.

VI. Expected POW Range Gains

A POW provides more power into the RFIC than the standard CW for the same input power. This suggests that an RF tag rectifying a POW should be able to power up at a location farther away than an RF tag rectifying the standard CW signal, provided the tag is limited by the diode threshold voltage in the charge pump rather than the total power draw of the RFIC. The read range gained from using a POW can be found using the linear power-up link budget for one-way power flow from the transmitter to the tag [8]:

$$P_{\mathrm{t}} = \frac{P_{\mathrm{T}} G_{\mathrm{T}} G_{\mathrm{t}} \lambda^2}{(4\pi r)^2} G_{\mathrm{POW}} \tag{2}$$

where P_{t} is the power received by the RFIC after charge pump boosting and rectification and P_{T} is the power transmitted by the reader from a transmit antenna with gain G_{T}. G_{t} is the gain of the RF tag receive antenna, and $\lambda^2/(4\pi r)^2$ is the free space distance and wavelength loss term. In this power-up link budget equation, G_{POW} is the POW gain, which represents the power gained by the RFIC from a POW relative to the conventional CW power. The POW gain is defined as

$$G_{\mathrm{POW}} = \frac{V_{\mathrm{O,POW}}^2}{V_{\mathrm{O,CW}}^2} \tag{3}$$

In this equation, $V_{\mathrm{O,POW}}$ is the output voltage of the charge pump with a POW input, and $V_{\mathrm{O,CW}}$ is the output voltage with a CW input. If standard CW is used instead of a POW, the POW gain reduces to 1, and the link budget equation remains unchanged. The POW gain is independent of the number of stages since the numerator and denominator of Eqn. 3 both depend on the number of stages, thus it cancels out.

A POW gain greater than 1 allows the tag to operate at a greater distance. According to Eqn. (2), the power received by a tag using a POW would be the same as the power received by a tag using standard CW if the POW tag was placed at a distance $\sqrt{G_{\mathrm{POW}}}$ times the distance of the CW tag. So the extra read range gained in meters (m) over a conventional CW excitation is

$$\text{Read Range Gain} = (\sqrt{G_{\mathrm{POW}}} - 1) r_{\mathrm{CW}} \ (\mathrm{m}) \tag{4}$$

TABLE II
IDEAL SIMULATED READ RANGE GAINS

Input Type	Output Voltage	POW Gain	Read Range	Read Range Gain
915 MHz CW	1.53 V	1 (0 dB)	9.4 m	-
2-subcarrier POW	2.38 V	2.4 (3.8 dB)	14.5 m	+5.1 m
4-subcarrier POW	3.47 V	5.1 (7.1 dB)	21.2 m	+11.8 m
8-subcarrier POW	5.08 V	11 (10.4 dB)	31.1 m	+21.7 m

where r_{CW} is the maximum read range in meters of a tag illuminated by conventional CW. This equation for read range gain gives the extra distance an RF tag can be placed away from the reader when using a POW.

The simulated read range gains are shown in Table II using the output voltage values from Table I in free space under ideal conditions for tag antenna matching and polarization matching. Assume that a minimum received power of -13 dBm, or $P_{\mathrm{t}} >$ 50.1 mW in the linear scale, is required for tag power-up at 915 MHz ($\lambda = 0.328$ m) [9]. Also assume the reader equivalent isotropic radiated power (EIRP $= P_{\mathrm{T}}G_{\mathrm{T}}$) is at the FCC's maximum allowed power level of 4 W. The passive RF tag uses an antenna with gain 2.1 dBi, or $G_{\mathrm{t}} = 1.62$ in the linear scale. With these assumptions, the 2-, 4-, and 8-subcarrier simple POWs from the simulations showed positive read range gains.

In Table II, the read range increased by more than 50% the original read range for the 2-subcarrier POW and more than doubled the read range for the 4- and 8-subcarrier POW. The POW gain can also be used for lowering the transmitted power from the reader or provide extra link margin to increase reliability. This example demonstrated that a simple POW can increase the read range of passive RF tags and/or provide extra link margin if lower transmitted power is desired.

VII. MEASUREMENT RESULTS

The goal of these measurements was to show the effectiveness of the POW on increasing read range. The experiment setup included designing a custom RFID reader, a standard Gen2 RFID tag, an observational receiver, and two types of POWs. To measure power input to the reader antenna and replace the reader local oscillator (LO) with a POW waveform, a custom RFID reader based on Figure 6 was constructed as shown in Figure 11. The R=>T baseband signal was implemented using MATLAB and a digital to analog converter (DAC). The R=>T baseband signal is a query and wait looped indefinitely until the measurement stops. The output of the DAC is hardwired to an external mixer along with a 915 MHz LO. This mixed signal is connected to an amplifier with 20 dB gain and maximum output of 15 dBm before gain compression begins [10]. The output of the amplifier is connected to a horn antenna aimed directly at the RFID tag.

The RFID tag used was the Alien ALN-9540 with an adhesive back, a global tag that complies with EPC Class 1 Generation 2 and ISO 18000-6C standards and can be used in the Americas, Europe, Middle East, Asia, and Africa [11]. This RFID tag was adhered vertically to a Styrofoam block

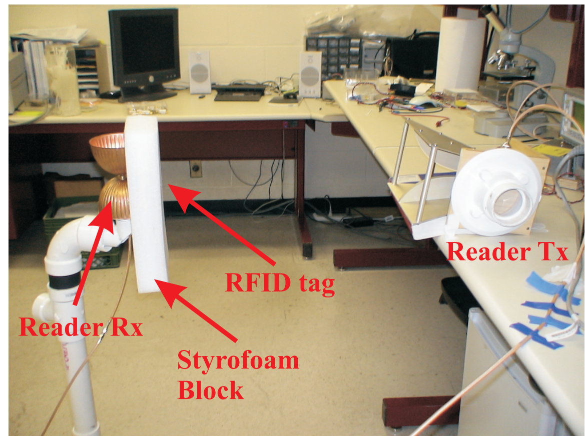

Fig. 12. Photograph of the stationary measurement setup. The RFID tag is placed on a styrofoam block supported by the receiver.

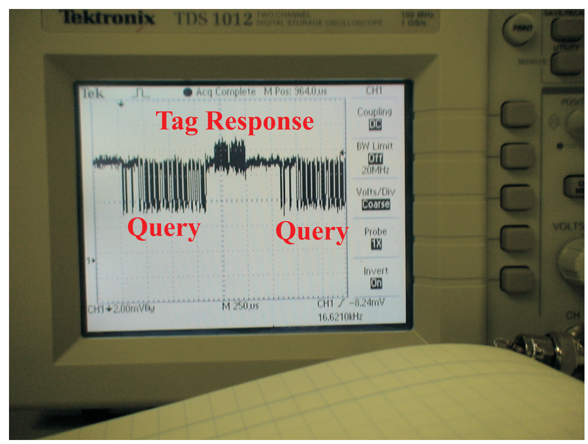

Fig. 13. Photograph of the oscilloscope screen showing the reader query waveform and the RFID tag's response.

to minimize polarization mismatch and was placed 46.4 cm away from the reader transmit antenna.

The backscatter response was measured using a dislocated reader receiver antenna. The system block diagram is shown in Figure 11, and a photograph is shown in Figure 12. It is a direct-conversion receiver with a custom bi-cone antenna that works between 600 MHz and 3 GHz. The R=>T communication signal and any RFID tag backscatter response is viewed on the oscilloscope. The receiver antenna was placed close to the tag so the received backscatter response was powerful enough and showed clearly on the oscilloscope screen, which is shown in a photograph in Figure 13.

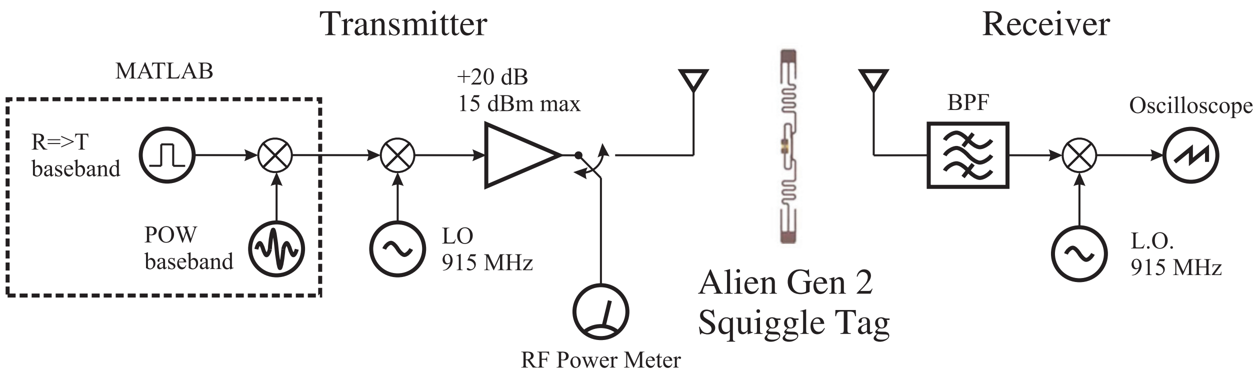

Fig. 11. RF front ends of the custom reader transmitter (left) and custom reader direct-conversion receiver (right) and RFID tag placed in the middle.

TABLE III
MEASURED POW READ RANGE GAINS

Input Type	Minimum Reader Transmit Power	Read Range	Read Range Gain
915 MHz CW	7 dBm	46.4 cm	-
4-subcarrier POW	5.5 dBm	55.2 cm	+8.8 cm
8-subcarrier POW	5.1 dBm	56.8 cm	+10.4 cm

The POW signals used for measuring read range gains were the 4-subcarrier simple POW and 8-subcarrier simple POW shown previously in Figures 5c and 5d. The read range gains of each were measured by finding the minimum reader transmit power required to get a tag response for each case while keeping the reader to tag distance fixed.

Table III shows the measurement results including distance gain of the POWs. The conventional CW required at least 7 dBm of reader transmit power for RFID tag turn-on. The 2nd order POW improved upon the conventional CW by 1.5 dB, requiring at least 5.5 dBm of reader transmit power, which corresponds to a 55.2 cm read range (19% increase). The 4th order POW improved it by 1.9 dB, requiring at least 5.1 dBm of reader transmit power, which corresponds to a 56.8 cm read range (24% increase).

The measured read range gains are more modest than the simulated read range gains for a number of reasons. Voltage regulation for the tag RFIC is more difficult under POW illumination due to a very large ripple in the charge pump output. Additional ripples may have confused demodulation circuitry, which is optimized for CW PIE. However, the POW provided a read range increase confirming the POW's effectiveness. Read range increased with higher order POWs confirming the claim of larger charge pump efficiency with larger input voltage.

VIII. CONCLUSION

The power optimized waveform (POW) concept, simulation results of charge pump circuits, implementation, and examples were presented. A POW can increase the power efficiency of charge pump based passive RF tags, which simultaneously increases read range and reliability. This new technique can be applied passive sensors or RFID including inductive HF RFID tags, as HF tags power up their internal circuitry with nearly identical rectifiers. Implementing a POW requires minimal changes within the reader and practically no change in the RF tag. The best POW types are the Gaussian or raised cosine POW due to their favorable spectral mask properties and efficiently-focused voltage amplitude in time. Implementing a POW in an RFID system allows extra tag power-up link margin, longer distance between the reader and tag, less transmitted power from the reader, or a combination of all three.

ACKNOWLEDGMENT

The authors would like to thank Daniel Dobkin for his constructive comments about passive UHF RFID related to this paper.

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