A Stacked Antenna Broad-band RFID Front-End for UHF and Microwave Bands

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ABSTRACT

A stacked antenna front-end for RFIDs is presented. Schottky diode based voltage doubler charge pumps are used on the front-end. The use of schottky diodes permits broadband operation for UHF (915MHz) as well as Microwave (2.45GHz). The entire chip has a low power EEPROM, digital state machine, clock recovery and data demodulation circuits; and the chip implements the ISO 18000-6B protocol for passive UHF (915MHz) operation. The chip is built on n-well, dual poly digital process with schottky diodes and EEPROM and comparisons are made between an unoptimized front-end built on 1um and an optimized front-end built on a 0.35 process. We provide a theoretical derivation for the superior orientational performance of a stacked antenna transponder as compared to a single antenna transponder. The tag front-end impedance is measured at UHF and Microwave bands for various powers and the threshold power for the tag is calculated. Based on the threshold power measured, the range of the tag is estimated and the omni-directional superiority of a stacked dipole is shown.

Categories & Subject descriptors

B.7.0 [**VLSI**]: General

General Terms

Algorithms, Design, Measurement

Keywords

RFID, dual front-end, UHF, Microwave, passive, schottky, cascade, stacked

1. INTRODUCTION

The concept of an RFID system that works based on the back-scattered signal from the tag has been around for a long time[1]. It is only recently that a tremendous interest in passive UHF RFID systems has developed[2,3]. This interest comes from the ability of RFID systems to permit real-time tracking of inventory that is essential to supply chain management systems and also the large ranges that are possible at UHF with reasonable form factors. The US Department of Commerce has indicated that there has been 1.25 Trillion US dollars worth of good sitting in idle inventory in the past year; software solutions for supply change inventory management have been used extensively, but owing to the lack of real-time inventory tracking, it has not made much impact. The real-time tracking capability that RFID brings has made it a highly viable technology to incorporate it in the supply-chain. Wal-Mart has mandated its suppliers to incorporate RFID technology by 2004. Very recently, the Department of Defense has stated that it would incorporate RFID chips that conform to the ISO standards for its Defense Logistics Agency (DLA). Based on the widespread interest in incorporating RFID, RFID chipsets may be the next biggest opportunity for the semiconductor industry. RFID transponders basically have a chip that is attached to a matched antenna. The transponder may have more than one antenna that is attached to the chip. When the transponder has two antennas where the voltages from the each antenna are added in series in the chip, it is referred to as the stacked antenna configuration. By connecting two antennas in series and adding the rectified voltages from them in series, an RFID tag can operate at twice the range of an RFID tag with a single front-end. Further more the tag can be made to have greater orientation insensitivity if the two antennas have orthogonal planes of polarization and this results in greater performance in the field where due to fluctuating fields, the tags are constantly passing through field nulls. This paper presents a schottky diode based broadband front-end.

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3. CHIP ARCHITECTURE

The entire chip has a RF front-end for rectifying the incoming RF signal, analog section for on-chip voltage regulation, clock recovery and data demodulation, digital state machine which implements the ISO 18000-6B protocol and a low power EEPROM module which can store upto 1k of bits. A high level schematic is shown in Figure 1.

In this paper we focus on the front-end of the chip and discussion of the other blocks is beyond the scope of this paper.

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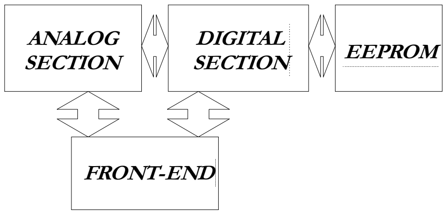

Fig 1. Top level block diagram of the chip

3.1 SINGLE ANTENNA CONFIGURATION Vs. STACKED ANTENNA

One of the major drawbacks of a passive RFID transponder with only a single dipole antenna is that it exhibits poor read/write ranges with different orientations. Even for the case when the base station is transmitting with a circularly polarized antenna, the transponder fails to be adequately powered when the tag is oriented in such a manner that the length of the dipole makes an angle with the plane of polarization. This impacts RFID system performance because tags that are not powered or loose power frequently will add considerable overhead and latency to the identification cycle.

A stacked antenna configuration alleviates the problem by having two antennas that are orthogonally polarized. And with a circularly polarized transmitting base station, at least one of the antennas will always be powered. In practice because the chip has a finite input

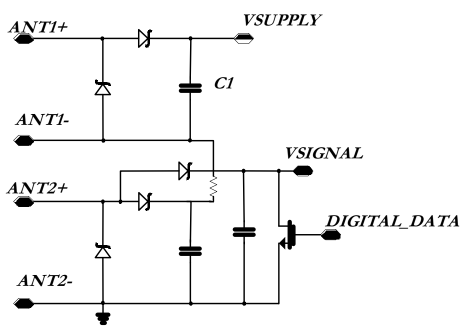

Fig 2a. Front-end circuit diagram for Testchip1

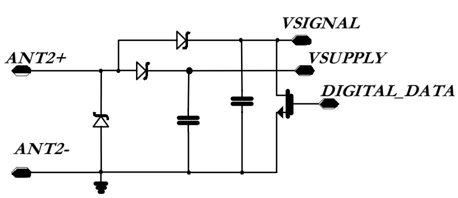

Fig 2b. Front-end circuit diagram for Testchip2

threshold power, it is possible that at certain orientations the power requirement is not met, still the performance of the stacked antenna is vastly superior to that of a single antenna configuration. This is explained further in the section on Tag Range.

3.2 BROAD-BAND FRONT-END

The tag front-end is often the simplest from the standpoint of circuit schematic but is often the bottleneck in obtaining high performance RFID chips. First of all, very good schottky diodes are required which have very little leakage characteristics and also exhibits little leakage at elevated temperatures. The parasitics on the front-end must be minimal; even a tiny parasitic capacitance of several 10s of femtofarads can drastically reduce the range of the tag, this requires very careful layout of the diodes. The smaller capacitance permits a high Q resonant circuit at the front-end and hence provides significant voltage multiplication. It can take several iterations on the fabrication line to get the required schottky diode characteristic, as well minimizing the parasitic capacitance. A well characterized schottky diode based front-end can work across a wide band of frequencies with a reasonable Q factor. This is not true for MOSFET based front-ends. Figure 2a shows a schematic of the front end for Testchip1. ANT1+ and ANT1-, and ANT2+ and ANT2- are connected to two separate antennas. The resistor between ANT1- and ANT2+ is used to provide isolation between the two antennas. VSUPPLY is the summed and rectified voltage from the two front-ends- this is the unregulated power supply for passive operation of the tag. VSIGNAL is the recovered signal from the tag and for this design it is taken from one front-end only. DIGITAL_DATA is the data that is being transmitted back to the base-station. This data is transmitted by ASK backscatter. The modulator transistor M1 when turned on provides a DC short and modulates the impedance of the antenna- this provides a differential back-scatter signal between the modulated and the unmodulated states. Some of the drawbacks for this circuit are that the parasitic capacitors for C1 couple through the substrate and may increase the front-end capacitance, thereby decreasing the Q of the circuit; also if one of the antennas is not powered, the corresponding capacitor on Vsupply will act as an open for the chip load current and over periods of time may reduce the voltage to the chip. This necessitates that there be a low-impedance DC path across the capacitors on Vsupply for current to flow. Figure 2b shows the optimized high performance front-end for Testchip 2, which is being currently under development for use in a stacked antenna configuration. Part of the optimization involved building a matrix of front-ends with schottky diodes of different areas. The only advantage that the 0.35um process used for Testchip2 over the 1um process for Testchip1 was a lower pad capacitance and much of the improvement was obtained through properly sized schottky diodes and improved layout that minimized parasitics.

A voltage doubler is used at the front-ends and the use of schottky diodes permits broadband operation of the tag. As a result the same front-end can be used for both UHF and Microwave bands.

4. TAG RANGE

This section calculates the range of the tag using the Friis transmission equation and ideal conjugate matched conditions. The range of a tag with a single front-end is given by [5]

$$R_r := \lambda \cdot \sqrt{\tau \cdot \left[\frac{(G_{tag} \cdot EIRP)}{8 \cdot \pi^2}\right] \cdot \left[\frac{(|Z_{chip}|)^2}{Re(Z_{chip})}\right] \cdot \left[\frac{1}{(0.5 \cdot V_{th} + V_{on})^2}\right]} \qquad \text{-Eq(1)}$$

where R_r is the range of the tag

λ is the wavelength of operation

EIRP is the power beamed out by the base station (4W)

Z_{chip} is the impedance of the chip

G_{tag} is the gain of the tag, 2db for a dipole

R_r is the range of the tag

V_{th} is the threshold voltage (2V)

τ is an impedance match factor (=1)

For a tag with two dipole antennas that are in the plane of polarization (assuming that the base station uses a circularly polarized antenna for transmission), and assuming that the antennas are orthogonal to each other (and thus have no interference between them) - if the two antennas are contributing equal power and if the chip impedances are same the range equation is modified (each antenna contributes half the voltage and hence the threshold voltage on each antenna is halved) to

$$R_r := \lambda \cdot \sqrt{\tau \cdot \left[\frac{(G_{tag} \cdot EIRP)}{8 \cdot \pi^2}\right] \cdot \left[\frac{(|Z_{chip}|)^2}{Re(Z_{chip})}\right] \cdot \left[\frac{1}{(0.25 \cdot V_{th} + V_{on})^2}\right]} \qquad \text{-Eq(2)}$$

If V_{ON} is considerably larger than V_{TH} then the range approximately doubles as compared to a single antenna transponder. We now examine the case of either of the two antennas having an angle (90^0 - θ) between the length of the dipole and the plane of polarization of the base station antenna. For this instance, the relationship between the range R_r and the peak induced voltage ($\theta=90^0$) is still given by Equation 1(and substituting V_r for V_{th}). When at a given range R_r, as the dipole makes an angle 90^0 - θ, with the plane of polarization, the induced voltage at either antenna is reduced from the peak value V_r to V_r. *f* where the factor *f* is the coefficient of V_r in Equation (4). This is because the gain of the tag antenna is reduced and in turn the induced voltage is also reduced. The gain of the antenna now becomes[6]

$$G_{tag}(\theta) = G_{tag} \frac{\cos\left(\frac{\pi \cdot \cos(\theta)}{2}\right)}{\sin(\theta)} \qquad \text{-Eq(3)}$$

And the induced voltage on each antenna is now reduced to

$$V(\theta) = V_r \cdot \left(\frac{\cos\left(\frac{\pi \cdot \cos(\theta)}{2}\right)}{\sin(\theta)}\right)^{0.5} \qquad \text{-Eq(4)}$$

$V(\theta)$ is the induced voltage at an angle θ and V_r is the peak induced voltage (when $\theta=90^0$) at the maximum range of the tag. At the range R_r, the chip will work only if the sum of the induced voltages from each antenna equals the minimum threshold voltage required on the chip, V_{th}. This condition is expressed as

$$\left(\frac{\cos\left(\frac{\pi \cdot \cos(\theta_1)}{2}\right)}{\sin(\theta_1)}\right)^{\frac{1}{2}} \cdot V_r + \left(\frac{\cos\left(\frac{\pi \cdot \cos(\theta_2)}{2}\right)}{\sin(\theta_2)}\right)^{\frac{1}{2}} \cdot V_r = V_{th} \qquad \text{-Eq(5)}$$

In practice the two front-ends need not have the same chip impedance. When the front-end impedances are different, the relationship between range R_r and the peak voltage induced on either antenna, assuming that both dipoles are in the plane of polarization of the base station antenna, is given by Equation(1) and at a given R_r the maximum possible induced voltage on each antenna is different owing to the differing front-end impedances. The condition for the chip to work is that the sum of the induced voltages from each antenna should equal the threshold voltage on the chip. This condition is expressed as

$$\left(\frac{\cos\left(\frac{\pi \cdot \cos(\theta_1)}{2}\right)}{\sin(\theta_1)}\right)^{\frac{1}{2}} \cdot V_1 + \left(\frac{\cos\left(\frac{\pi \cdot \cos(\theta_2)}{2}\right)}{\sin(\theta_2)}\right)^{\frac{1}{2}} \cdot V_2 = V_{th} \qquad \text{-Eq(6)}$$

where V_1 and V_2 are the peak induced voltages on each antenna(when $\theta = 90^0$) and are given by Equation (1). In order to incorporate the effect of range, we further modify this equation. Assuming that either of the two induced voltages V_1 or V_2 is much greater than the turn on voltage of the schottky diodes, the equation is further modified to

$$\left[\frac{\sin\theta_1}{\cos\left[\left(\frac{\pi}{2}\right)\cdot\cos\theta_1\right]}\right]^{\frac{1}{2}} \cdot V_1 \frac{R_r}{V_{th}} + \left[\frac{V_r \cdot \sin\theta_2}{\cos\left[\left(\frac{\pi}{2}\right)\cdot\cos\theta_2\right]}\right]^{\frac{1}{2}} \cdot V_2 \frac{R_r}{V_{th}} = R$$

-Eq(7)

where V_1 is the induced voltage at R_r on antenna 1 and V_2 is the induced voltage at R_r on antenna 2(when θ_1, $\theta_2 = 90^0$). This equation gives the range of the tag R_r for any orientation θ_1 and θ_2. When either of V_1 and V_2 are zero, it reduces to the case of a transponder with a single antenna.

5. TAG IMPEDANCE MEASUREMENT

The impedance measurement setup consists of Cascade Fixed Pitch (FPC) probes that are used to make landings on the RF pads of the chip. The probes are connected to an HP1987 Broadband Network Analyzer and the impedance is measured after calibration with a ceramic impedance substrate standard (ISS).

The impedance is measured for various incident RF powers ranging from -10dBm to 5dBm. Since the threshold voltage of the chip is known, the impedance is measured at the point where the peak RF voltage reaching the chip is $0.5V_{TH} + V_{ON}$. The voltage developed on the chip is given by

$$P_{tag} := P_{source}\left[1 - (|\rho|)^2\right] \qquad \text{-Eq(8)}$$

Where ρ is given by

$$\rho := \frac{Z_L - Z_0}{Z_L + Z_0} \qquad \text{-Eq(9)}$$

The impedance at the threshold point is critical for conjugate matching the antenna to the chip and needs to be determined with great accuracy. The impedance measurements are summarized in Tables 1-3. In this experimental prototype, the signal decoding circuitry is only connected to one antenna (Antenna 1). As a result for the tag to communicate with the base-station, Antenna 1 should always be powered. However in an actual chip, the signal decoding circuitry may be coupled to both antennas if the chip is to independently work from either antenna.

Table 1. The measured impedance and the calculated voltage for Antenna 1 at various powers and frequencies

Incident power at 915MHz (dBm)	*Impedance(Real)*	*Impedance(Imaginary)*	*Power absorbed by the load(dBm)*	*Peak RF voltage across the front-end*
-10	41	-776	-29.04	0.2
-5	51	-791	-22.95	0.35
0	40	-779	-18.86	0.63
3	99	-788	-12.12	0.88
5	200	-760	-7.04	1.1

Incident power at 2.4GHz (dBm)	*Impedance(Real)*	*Impedance(Imaginary)*	*Power absorbed by the load(dBm)*	*Peak RF voltage across the front-end*
-10	33	-293	-21.48	0.19
-5	32	-299	-16.77	0.34
0	33	-303	-11.75	0.61
3	3	39	-306	-8.15
5	55	-302	-4.68	1.08

6. TAG IMPEDANCE MEASUREMENTS AND RANGE DETERMINATION

Tables 1 and 2 present the impedance of the two antennas for various RF powers in the two frequency bands of interest; the voltage is that is present on the front of the chip is twice the peak RF voltage in the table minus the twice the diode drop(due to the voltage doubling action of the charge pump). The chip DC threshold voltage of operation is 2V (V_{TH}). If antenna 1 alone was powering the tag, then the input threshold RF power into the chip is -7 and -5 dBm at UHF(as seen from table 1) and Microwave bands. If antenna 2 alone were to power the chip, the input threshold RF power into the chip is 0 and 3dB at the UHF and Microwave bands respectively. This means that for the same gain for the matched antennas, the range of the tag with antenna 2 alone would be less than half the range of the tag with antenna 1. Using the range equations developed in the above sections, the range of the tags is calculated based on the impedance measurements.

Table 2. The measured impedance and calculated voltage for Antenna 2, at various powers and frequencies

Incident power at 915MHz(dBm)	*Impedance(Real)*	*Impedance(Imaginary)*	*Power absorbed by the load(dBm)*	*Peak RF voltage across the front-end*
-10	60	-141	-14.26	0.17
-5	59	-145	-9.45	0.31
0	58	-148	-4.61	0.55
5	58	-153	0.19	0.98

Incident power at 2.4GHz(dBm)	*Impedance(Real)*	*Impedance(Imaginary)*	*Power absorbed by the load(dBm)*	*Peak RF voltage across the front-end*
-10	38	-68	-12.11	0.14
-5	37	-69	-7.22	0.25
0	37	-69	-2.22	0.45
3	37	-311	-8.49	0.87
5	37	-71	2.69	0.8

Table 3. The measured impedance and calculated voltage for Test-chip2, at various powers and frequencies

Incident power at 915MHz(dBm)	*Impedance(Real)*	*Impedance(Imaginary)*	*Power absorbed by the load(dBm)*	*Peak RF voltage across the front-end*
-10	8.7	-661	-35.24	0.17
-5	6.8	-630	-30.59	0.32
0	8.32	-659	-25	0.57
5	22.3	-722.2	-16.41	1.03

Incident power at 2.4GHz(dBm)	*Impedance(Real)*	*Impedance(Imaginary)*	*Power absorbed by the load(dBm)*	*Peak RF voltage across the front-end*
-10	12.99	-247	-25.49	0.16
-5	13.27	-233	-20.02	0.29
0	14.13	-242	-14.96	0.52
5	16.12	-262.5	-9.86	0.94

The range for Test-chip 1 when powered by Antenna 1 (using Equation 1 and Table 1) = 4m

The range for Test-chip 1 when powered by Antenna 2 (using Equation 1 and Table 2) = 1.68m

The range for Test-chip 2(using equation 1 and Table 3) = 9.64m

The range for a stacked antenna configuration using Test-chip 2(work in progress) = 19.2m

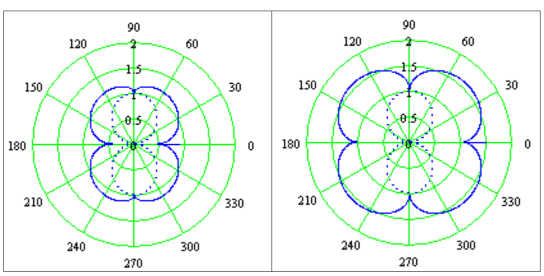

Figure 3. Range (normalized to the range of a single antenna ta; polar plots showing the omni-directional performance of a stacked antenna-solid line vs. that of a single antenna configuration-dotted line (plot for Testchip1 is on the left and plot for Testchip2 is on the right)

Note that in Testchip1, the backscatter modulator and the signal decoder is only present on one antenna, so there should always a small amount of RF power incident on this antenna to exchange data with the base-station. Based on these range calculations we present the range-directionality plots (Figure 3) for Testchip1 (left) and Testchip2 side by side, based on Equation (7); in this plot, the antennas are assumed to be orthogonal and in a plane that is orthogonal to the plane of polarization- the tag is rotated in this plane; the range of the tag is plotted as a function of the angle θ_1 and θ_2 defined earlier.

7. SUMMARY

A stacked antenna front-end for RFID chips is presented. The range equations for various orientations of the tag are derived. The impedance of the front end for various source powers is measured and the optimum power required by the tag to develop the needed voltage is calculated. The front-end is built on an n-well CMOS digital process with schottky diodes, EEPROM and dual poly layers-the unoptimized Testchip1 is built on a 1um process and the tuned front-end Testchip2 is built on a 0.35 process. The use of schottky diodes in the front-end permits broadband operation of the same front-end at UHF and Microwave bands. We present theoretical equations that prove the superior omni-directional performance of a stacked antenna chip and based on these equations and measured RF front-end impedances, the range of the chip for various configurations is calculated. The optimized front-end for Testchip 2 is being used for building a stacked antenna configuration currently under development. Both chips have on chip analog and digital circuitry that implement the ISO-180006B protocol.

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