An Enhanced-range RFID Tag Using an Ambient Energy Powered Reflection Amplifier

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***Abstract*—A great challenge in UHF RFID systems consists of increasing their operating range. In this work, a circuit topology consisting of a reflection amplifier and a passive coupler is proposed to both amplify the input signal to the tag as well as the backscattered signal towards the reader. System analysis is provided to estimate the performance requirements of the proposed circuit. The amplifier is optimized in order to maximize its gain while minimizing its dissipated power, thus allowing for low-power operation by using ambient energy harvesting devices such as solar cells. The circuit is compatible with commercial UHF RFID tags and is implemented using low-cost inkjet printing fabrication. Prototypes of the various circuit components are fabricated and evaluated demonstrating the feasibility of the proposed system. Interesting results are showcased for tag efficiency improvement through such non-conventional front-end designs.**

***Index Terms*—UHF RFID, range increase, low-power, reflection amplifier, inkjet printing.**

I. Introduction

Passive UHF Radio Frequency Identification (RFID) is a low cost technology which has numerous applications in retail and logistics [1]. Due to the capability of introducing sensing functionality to RFID tags with little or no degradation in their power dissipation, by utilizing concepts such as passive antenna sensing and taking advantage of novel ‘smart’ thin film materials such as carbon nanotubes, graphene oxides and others [2], [3], UHF RFID systems are currently being considered for a number of additional applications related to monitoring in agriculture, security and food industries. RFID technology presents itself as an excellent candidate for implementing the Internet of Things.

On one hand, remote powering of passive UHF RFID tags using wireless power transmission through a reader circuit is an exciting feature of the technology eliminating the necessity of batteries. On the other hand, the need to remotely power the utilized RFID chips, which typically have sensitivities of -20dBm to -16dBm, by a reader signal of 4W EIRP, limits the practical tag operating range to a few meters [1]. Consequently, methods for increasing the range of such tags by exploring ambient energy harvesting technologies are of particular interest, since the increase in reading range has a direct effect in reducing the associated cost related to the number of required readers to cover large areas. Previous work has proposed the use of solar energy harvesting to power UHF RFID tags, as an auxiliary DC power supply [4], or as an additional RF signal by efficiently converting the DC power from the solar cells to RF [5]. Recently, interesting techniques of range increase have been also presented, by exploiting non-conventional reader architectures for backscatter radio/RFID systems [6].

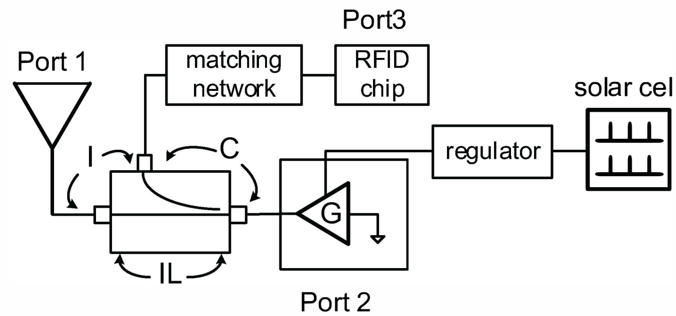

Fig. 1. Enhanced range passive RFID tag.

In this work, a circuit consisting of a reflection amplifier and a power splitter is proposed to amplify both the reader signal at the input of a commercial UHF RFID chip, and the backscattered signal towards the reader. The dissipated power of the amplifier is minimized in order to be effectively powered for example by low cost solar cells and under low illumination conditions. A reflection amplifier [7] and a dual reflection-transmission amplifier [8] have been proposed for semi-passive RFID tags operating at 5.8 GHz and 5.25 GHz respectively, without setting strong constraints to the amplifier dissipation. It is noted that in [8] modulation at the amplifier output is achieved by controlling (switching on and off) the amplifier bias. In this work, the impedance switching of the RFID chip itself acts as a load modulator to the amplifier, changing the overall system reflection coefficient Γ at the antenna port. This sets the proposed circuit directly compatible with commercial passive RFID tag chips. In the following sections, the proposed system analysis is presented, followed by the design of the various passive components and the amplifier. Inkjet printing is used to fabricate low cost prototypes that are evaluated to demonstrate the feasibility of the design.

II. System Analysis

The proposed tag consists of an antenna, a power splitter, a reflection amplifier which can be powered by a solar cell

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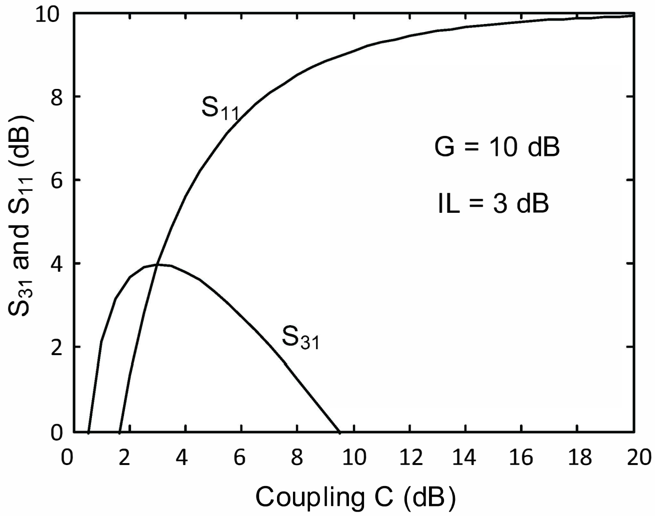

Fig. 2. Effect of coupling factor on system performance for amplifier gain $G = 10\text{dB}$.

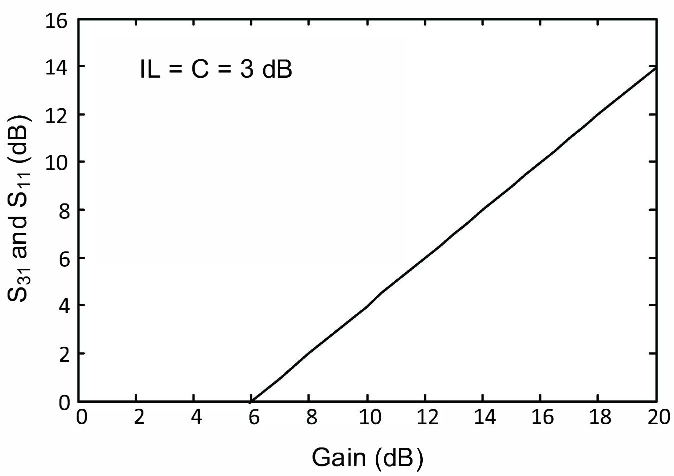

Fig. 3. Effect of amplifier gain on system performance for insertion loss and coupling factor equal to 3dB.

and voltage regulator, and an RFID chip (Fig. 1). A simple system analysis setup has been created in Agilent ADS based on Fig. 1 and the effects of the amplifier gain and coupling factor have been investigated. Fig. 2 shows the effect of the coupling factor in the system s-parameters for amplifier gain of $G = 10\text{dB}$. Maximum power is delivered to the RFID chip when the coupling factor is equal to the insertion loss ($C = \text{IL} = 3\text{dB}$). Furthermore, a minimum amplifier gain of $\text{IL} + C$ (dB) is required, in order for the circuit to have a performance gain over a standard passive tag circuit. This is shown in Fig. 3 for $C = \text{IL} = 3\text{dB}$.

Let one consider an operating frequency of 900 MHz, a reader transmit power of $P_T = 1\text{W}$ and a circularly polarized reader antenna with gain $G_T = 6\text{dB}$ (in total, 4W EIRP). Furthermore, let one consider a tag chip, with sensitivity $P_{\text{th}} = -18\text{dBm}$, matched (transmission coefficient $\tau = 1$) to a linearly polarized tag antenna of gain $G_R = 0\text{dB}$. The circularly polarized reader antenna and linearly polarized tag antenna lead to a polarization mismatch of $\chi = 0.5$. Using the Friis transmission formula for free space

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_T G_T G_R\ \tau\ \chi}{P_{\text{th}}}}, \tag{1}$$

one can estimate that the tag can be activated at a distance of 9.42m. The proposed tag circuit assuming an amplifier with gain $G = 10\text{dB}$ and $\text{IL} = C = 3\text{dB}$, leads to a $S_{31} = 4\text{dB}$ (Fig. 2), which effectively reduces the tag sensitivity to -22 dBm and its activation range to 11.86 m; this corresponds to a range increase of 25.9%.

To increase the range of a tag, its bit-error-rate (BER) at the reader has to be minimized for a given reader-emitted power. In [9] it is shown that the tag BER at the reader is directly related to the reflection coefficient 'distance'

$$|\Delta\Gamma| \triangleq |\Gamma_0 - \Gamma_1|, \tag{2}$$

where Γ_0 is the reflection coefficient at the antenna terminal when the tag input impedance is Z_0 (i.e. bit '0') and Γ_1 is the reflection coefficient when the tag input impedance is Z_1, respectively. A usual case is that passive RFID tags are matched for bit '0' ($Z_0 = Z_a^*$) and shorted for bit '1' ($Z_1 = 0$) [10]. Z_a is the antenna input impedance, and Z_a^* is its complex conjugate. In this case, $\Gamma_0 = 0$ and $\Gamma_1 = 1$, based on the formula [11]:

$$\Gamma_i = \frac{Z_i - Z_a^*}{Z_i + Z_a}, \qquad i = 0, 1. \tag{3}$$

According to the aforementioned, the reflection coefficient difference amplitude for passive RFID tags is $|\Delta\Gamma| = 1$. Thus, to achieve a performance gain, a distance greater than unity has to be achieved, through the use of the proposed topology.

III. Passive Circuit Design

A Wilkinson power divider has been designed for interfacing the RFID chip, reflection amplifier, and system antenna. The divider is designed for transferring power from the system antenna to the reflection amplifier, then from the reflection amplifier to the tag chip and vice versa. The power divider is simulated in HFSS and then fabricated with inkjet printed technology. Four layers of conductive silver ink are printed on low-cost photo paper substrate to achieve high conductivity of the structure (Fig. 4). The S-parameters of the fabricated Wilkinson power divider have been measured with a lab vector network analyzer (VNA) end exported for post-processing.

A simple antenna is also designed and implemented with conductive ink on photo paper. The antenna is a monopole tuned at 915 MHz and has a return loss better than 15dB between 895MHz and 942MHz. The tag chip utilized in the design is also mounted on paper substrate along with an LC matching network to transform its complex impedance to the system characteristic impedance of 50Ω. The measured sensitivity of the matched tag chip is -16dBm. The monopole antenna and the tag chip with the corresponding matching network prototypes can be seen in Fig. 4.

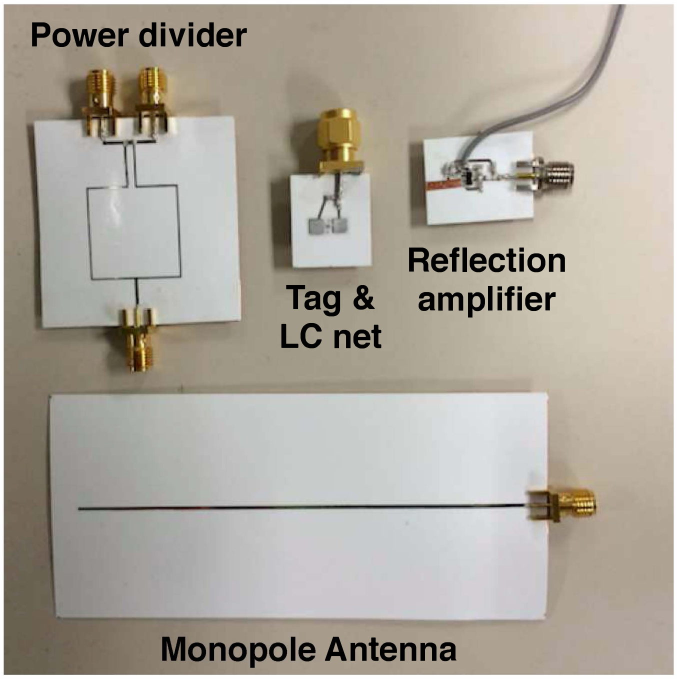

Fig. 4. Inkjet printed prototypes.

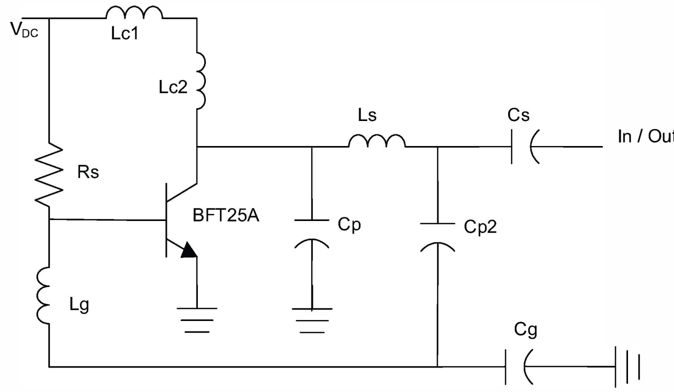

Fig. 5. Reflection amplifier circuit diagram.

TABLE I
REFLECTION AMPLIFIER CIRCUIT COMPONENT VALUES.

Component	Value	Component	Value
C_s	56pF	$L_{c1} + L_{c2}$	130nH
L_s	18nH	L_g	18nH
C_p	1.2pF	C_g	1.0pF
C_{p2}	1.8pF	R_s	12kΩ

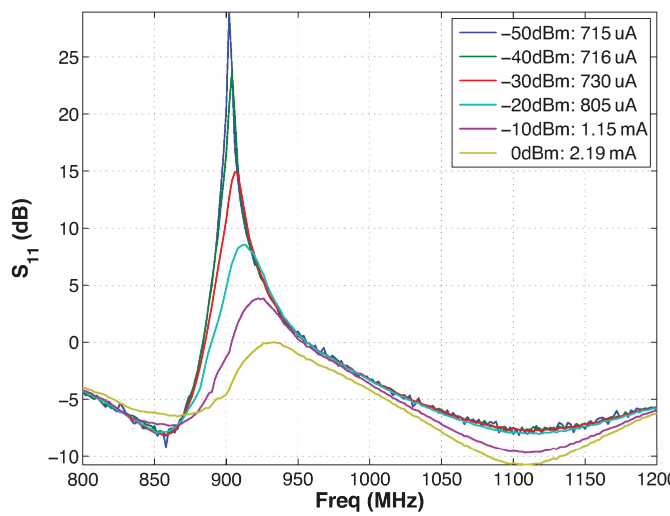

Fig. 6. Reflection amplifier gain as a function of the input power level.

IV. REFLECTION AMPLIFIER

The reflection amplifier circuit is obtained by first designing an oscillator circuit using harmonic balance analysis and subsequently properly biasing it in order to present negative resistance without fulfilling the necessary conditions to start oscillating. The various components of the original oscillator circuit are tuned using large signal S-parameter simulation in order to maximize the amplifier gain at a desired frequency and input power. The circuit diagram of the reflection amplifier is shown in Fig. 5 and the various component values are listed in Table I. The implemented circuit can be seen in Fig. 4, where all lumped components have been placed on paper substrate. To guarantee that the implemented reflection amplifier is biased properly so that it does not oscillate, its output is observed with a real-time spectrum analyzer, while modifying its bias voltage. The maximum DC bias applied is 0.83V before the amplifier starts oscillating. The amplifier draws 800μA at -20dBm input power, corresponding to a dissipation of 664μW. This power is sufficiently low to be obtained using ambient energy harvesting [4], [5], [12]. Thus, the implemented amplifier is practical for use in low power RFID applications. The amplifier gain is measured using a vector network analyzer (VNA) at the 800MHz–1.2GHz frequency region. The measured S_{11} values are provided in Fig. 6, where it can be seen that the amplifier gain is approximately 8dB for an input power as high as -20dBm, while it may reach up to 29dB for an input power as low as -50dBm. This high gain operation can be beneficial at long ranges, where the power induced at the tag antenna is very low.

V. PERFORMANCE IMPROVEMENT

The improvement in performance of an RFID system can be evaluated by comparing the reflection coefficient difference amplitude $|\Delta\Gamma|$ between the proposed system topology and a classic tag-antenna system that does not include any amplifier. An ADS model has been built to compare among the two systems. For including all realistic system losses and mismatches, the VNA-measured S-parameters for the reflection amplifier and Wilkinson divider have been imported to the model (Fig. 7). For the conventional RFID tag, an antenna terminal is interfaced directly to a load that is either matched

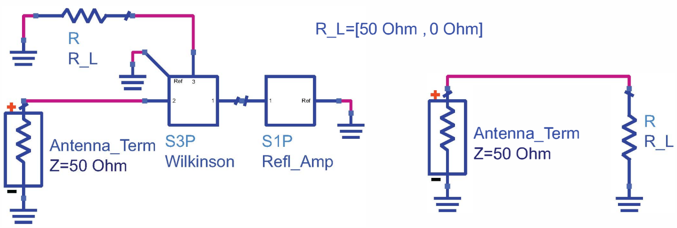

Fig. 7. Compared tag front-end models. Left: proposed system with reflection amplifier. Right: conventional tag.

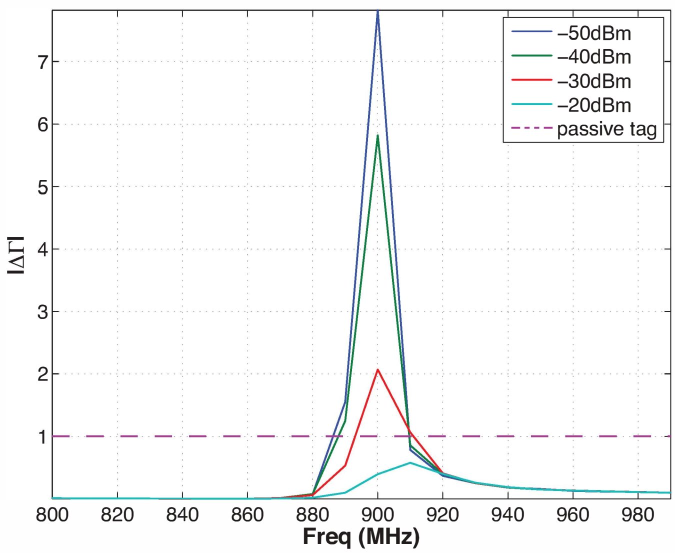

Fig. 8. Reflection coefficient difference amplitude as a function of the reflection amplifier input power level.

to the antenna (50Ω), or is shorted to the ground (0Ω). For the proposed system, the reflection amplifier is connected to Port 1 of the Wilkinson, an antenna terminal has been set to Port 2 , and a modulating load to Port 3. The load takes the same values with the conventional tag case.

The reflection coefficient difference amplitude $|\Delta\Gamma|$ is obtained via simulation between 800MHz–1GHz and is plotted as a function of frequency and power level in Fig. 8. It can be concluded that for input power levels to the amplifier of under approximately -25dBm, there is improvement over the value $|\Delta\Gamma| = 1$ for passive tags (dashed line). The fact that the improvement is higher for lower input power levels is in agreement with the fact that the reflection amplifier gain also increases for low power levels (Fig. 6). This result shows that an improved BER at the reader can be achieved at low amplifier input power levels for the same reader-emitted power, compared to a conventional tag. This in turn provides for higher operating ranges for a given BER value, when the proposed system is utilized.

VI. Conclusion

A new tag topology based on the use of a reflection amplifier and coupler circuit has been proposed, able to provide enhanced RFID tag range. The circuit is compatible with commercial RFID tag chips and can operate using ambient energy harvesting devices. The system components have been fully implemented on paper substrate using inkjet printed technology to demonstrate the low-cost nature of the proposed design. It has been shown that with this low-cost system an improvement to the reflection coefficient difference amplitude of the tag can be achieved. The latter is a parameter directly related to the BER at the reader, thus affecting the operating range of a tag. The proposed system appears to have a strong potential for efficiency improvement of backscatter radio/RFID tags and opens a field for research on careful design and optimization of non-conventional, enhanced-range RF tag front-ends. The system presented in this work could consist a perfect candidate for combining with recent work on the backscatter communication field for non-conventional reader architectures, to achieve even larger improvements on tag operating ranges.

Acknowledgment

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References

[1] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication*, 3rd ed. New York, NY, 10158: John Wiley & Sons, Inc., 2010.

[2] L. Yang, Z. Rongwei, D. Staiculescu, C. P. Wong, and M. M. Tentzeris, "A novel conformal RFID-enabled module utilizing inkjet-printed antennas and carbon nanotubes for gas-detection applications," *IEEE Antennas Wireless Propagat. Lett.*, vol. 8, pp. 653–656, 2009.

[3] V. Lakafosis, A. Rida, R. Vyas, L. Yang, S. Nikolaou, and M. M. Tentzeris, "Progress towards the first wireless sensor networks consisting of inkjet-printed, paper-based RFID-enabled sensor tags," *Proc. IEEE*, vol. 98, no. 9, pp. 1601–1609, Sep. 2010.

[4] A. P. Sample, J. Braun, A. Parks, and J. Smith, "Photovoltaic enhanced UHF RFID tag antennas for dual purpose energy harvesting," in *IEEE Intl. Conf. on RFID 2011*, Orlando, FL, Apr. 2011, pp. 146–153.

[5] A. Georgiadis and A. Collado, "Improving range of passive RFID tags utilizing energy harvesting and high efficiency class-E oscillators," in *6th IEEE European Conf. on Antennas and Propagation (EuCAP)*, Prague, Czech Republic, Mar. 2012, pp. 3455–3458.

[6] J. Kimionis, A. Bletsas, and J. N. Sahalos, "Increased range bistatic scatter radio," *IEEE Trans. Commun.*, 2014.

[7] P. Chan and V. Fusco, "Bi-Static 5.8GHz RFID range enhancement using retrodirective techniques," in *41st European Microwave Conference (EuMC)*, Manchester, United Kingdom, Oct. 2011, pp. 976–979.

[8] ——, "Full duplex reflection amplifier tag," *IET Microwaves, Antennas & Propagation*, vol. 7, no. 6, pp. 415–420, Apr. 2013.

[9] A. Bletsas, A. G. Dimitriou, and J. N. Sahalos, "Improving backscatter radio tag efficiency," *IEEE Trans. Microwave Theory Tech.*, vol. 58, no. 6, pp. 1502–1509, Jun. 2010.

[10] D. M. Dobkin, *The RF in RFID: Passive UHF RFID in Practice*. Newnes (Elsevier), 2008.

[11] K. Kurokawa, "Power waves and the scattering matrix," *IEEE Trans. Microwave Theory Tech.*, vol. 13, no. 2, pp. 194–202, 1965.

[12] R. J. Vyas, B. B. Cook, Y. Kawahara, and M. M. Tentzeris, "E-WEHP: A batteryless embedded sensor-platform wirelessly powered from ambient digital-TV signals," *IEEE Trans. Microwave Theory Tech.*, vol. 61, no. 6, pp. 2491–2505, Jun. 2013.

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