Design, Analysis and Performance Evaluation of a UHF RFID Forward-Link Repeater

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***Abstract*—The range of UHF-RFID systems, involving passive tags, is typically limited by the tag's RF harvesting circuitry. In this paper a forward-link UHF RFID repeater is proposed. The repeater amplifies the reader-to-tag carrier signal. Then, a passive RFID tag can be successfully identified from a much larger distance, compared to current technology, by exploiting the sensitivity of the reader. The proposed repeater consists of low-cost components; namely a pair of antennas, a low-noise amplifier and passive electronics. The proposed design also accounts for out-of-band emissions and the limitations posed by the maximum effective isotropic radiated power of the EPC UHF Gen2 standard. In contrast to prior-art, it can be deployed with any commercial RFID reader. Link-budget analysis reveals i) that the location of the repeater is of great importance to the system, ii) the range depends on the reverse link and not on the forward, as in typical RFID technology and iii) optimum performance can be achieved with bistatic RFID readers and RFID tags, capable of harvesting RF power at higher input power-levels. It is shown that with common, commercial, monostatic RFID technology, a maximum range of 80m can be achieved. By deploying bistatic configurations, which allow for improved reader's sensitivity, the read-range could be extended to 350m. By "tuning" the tag's front-end to achieve good matching for increased incident power levels, the expected range could be increased to 2km. Experimental results validate the performance of the proposed repeater and reveal how the link budget is affected by the tag's front-end. 73m measured range is experimentally achieved with commercial monostatic RFID equipment.**

***Index Terms*—Radiofrequency identification, RFID tags, Repeater.**

I. Introduction

RADIO Frequency Identification (RFID), involving battery-less (passive) tags, is in principle a short-range communications technology. Its inherent advantage - the absence of a power source with a finite expiration date - strongly affects the maximum read-range [1]; i) due to the round-trip path, backscattered power decays with the 4^{th} power of distance, ii) the tag's front-end comprises a rectifying circuit which demands a necessary minimum voltage to be powered up, while iii) the reader must continuously emit a carrier signal (for powering up the tag) which affects its own sensitivity at reception of the backscattered signal [2]- [3]. Prior-art on increasing the range of passive RFID networks is focused on optimizing the transmitted/backscattered waveforms [4]- [5], harvesting harmonic content at higher frequency, generated by the tag [6]- [7], deploying multi-antenna configurations [8] or increasing the available power, while adhering to the maximum Effective Radiated Power (EIRP) constraints of the standard [9]- [14]. Available power at the tags is increased by deploying bistatic, [9], or generally multistatic, [10]- [13], reader configurations with multiple emitters at the vicinity of the tags, or harvesting energy from other sources, [14]. The tag is powered-up and the "distant" reader successfully receives information from the tag, exploiting its improved sensitivity, compared to a monostatic reader. A good example is the "Mojix" commercial system, [11]- [12], which is based on controlling a distributed network of emitters through a wired or wireless infrastructure, while a single reader receives the backscattered signal from the "distant" tags.

The multistatic configurations aim: i) to separate the reader into two distinct RF blocks (transmitter and receiver), such that the sensitivity of the reader is improved and ii) to bring the energy close to the RFID tag (by placing the emitter closer to the tags). Due to the full-duplex nature of RFID communications, the sensitivity of the reader is limited by its ability to discriminate the small modulated backscattered signal in the presence of the large carrier signal transmitted by the reader and its structural echoes by the environment [2]- [3]. As a result, dynamic self jamming cancellation techniques and high dynamic-range in the receiver's front end are required [3]. In monostatic readers, the leaked carrier from the transmitter RF block (at 30dBm) enters the receiver's block, attenuated by only 20dB to 30dB. Further isolation is accomplished by adaptive self-jamming cancellation circuits (up to 50dB), achieving a sensitivity in the order of -80dBm. In the case of bistatic (or multistatic) configurations the magnitude of the undesired carrier signal, entering the receiver's chain, depends on the spacing between the transmit-receive antennas and the corresponding radiation patterns. It is generally much smaller than the circulator's output power of a monostatic reader. Again, adaptive cancelation circuits are deployed, and the achieved sensitivity could be comparable to typical half-duplex systems for 1MHz channel bandwidth.

Interestingly, the full-duplex nature of RFID technology, affects in the same manner the potential to deploy a full duplex repeater [15]- [18]. In a two-way repeater, there is one amplifier, for each direction of the link (reader-to-tag and tag-to-reader). Isolation between the output and the input of each amplifier must be larger than amplification; otherwise the amplifier would oscillate and rapidly saturate. Due to the presence of the second amplifier, isolation cannot be accomplished by electromagnetically decoupling the output from the input. Instead, adaptive cancellation must be deployed, as described previously for the RFID reader. However, this

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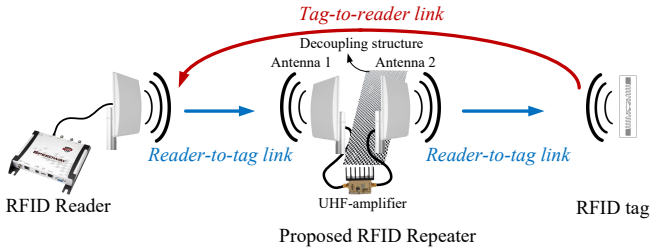

Fig. 1. Representation of the proposed repeater.

time, two such circuits are necessary; one for the forward and one for the backward link. Adaptive cancellation of the backward link is even more challenging, if at all possible, since the circuit must be able to cancel the small modulated backscattered signal coming from the tag, in the presence of the strong RF carrier. Even if this is accomplished, the tag-to-reader amplifier causes another undesired effect. Apart from the modulated backscattered signal, it also amplifies reflections of the carrier signal originating from the environment [3], making them comparable or stronger than the RFID reader's transmitted carrier which leaks into the receiver's front-end, further worsening the sensitivity of the reader, as described in the previous paragraph. Overall, such a complex device would doubtfully offer any advantage over placing an additional RFID reader at the potential location of the "full duplex" repeater, since the overall cost would probably be comparable.

A forward repeater for UHF RFID was presented in [19], where the goal was to increase the forward link budget towards an RFID implant and in [20] for a 2.43GHz, where the focus is on achieving the desired antenna isolation.

In this paper a forward-link-only repeater is proposed. The repeater will increase the reader-to-tag link budget. It consists of a pair of antennas, facing opposite directions and a low-noise UHF amplifier (LNA), as shown in Fig. 1 (actually filtering and power limiting are also deployed, as explained in the manuscript). Isolation between the output and the input can be achieved by properly grounding and spacing the antennas; adaptive cancellation is unnecessary. Such a low-cost repeater can deliver enough power to the tag at any distance, since the designer can use arbitrarily directive antennas, and a proper amplifier. Furthermore, multiple repeaters can be used in cascade. As a result, successful identification of the tag depends on the tag-to-reader link. The proposed solution is directive; Line-Of-Sight conditions are needed for all involved links: i) reader-to-repeater, ii) repeater-to-tag, iii) tag-to-reader. Under such geometrical conditions, by deploying multiple repeaters, the installation cost for large areas is reduced significantly.

The design constraints of the repeater are analyzed in Section II, considering out-of-band emissions and maximum EIRP limitations imposed by the standard. A link-budget analysis is presented in Section III, where the importance of the sensitivity of the reader is shown. The proposed repeater can increase the read-range of passive commercial tags to 80m with a monostatic RFID reader, 350m with a bistatic RFID reader and 2km, assuming better design of the tag's IC. Measurements of commercial RFID tags with and without

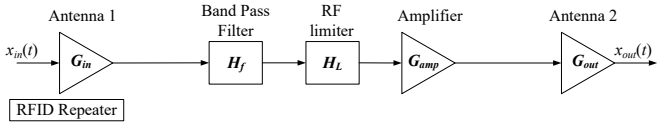

Fig. 2. Block diagram of proposed repeater.

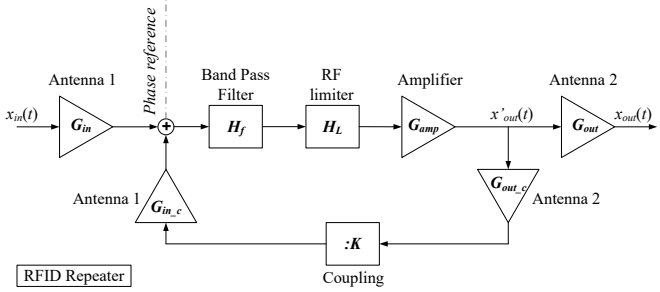

Fig. 3. Representation of repeater with coupling.

the repeater are given in Section IV. Commercial passive RFID tags are successfully identified 73m from the reader. Concluding remarks are presented in Section V.

II. Proposed Repeater

A block diagram of the proposed repeater is shown in Fig. 2. It consists of the following elements: i) a directional antenna of gain $G_{in}(f)$ (antenna 1 in Fig. 1), facing the reader's antenna, ii) a bandpass filter of transfer function $H_f(f)$, iii) an RF power limiter with transfer function $H_L(f)$, iv) a bandpass high frequency low-noise amplifier of gain $G_{amp}(f)$ and v) a directional antenna of gain $G_{out}(f)$ (antenna 2 in Fig. 1), facing the opposite direction, where f is the frequency. The incident signal from the reader is received from antenna 1, filtered by the filter, limited if the incident RF power is above a given threshold, amplified by the amplifier and re-transmitted from antenna 2.

Due to electromagnetic coupling, part of the transmitted signal from antenna 2 is received by antenna 1, is again amplified and re-transmitted by antenna 2, thus forming the closed loop model, shown in Fig. 3. As the two antennas face opposite directions, only a small portion of the signal radiated by antenna 2 is coupled back to antenna 1, represented by gains $G_{out\_c}(f)$ and $G_{in\_c}(f)$ respectively in Fig. 3. Finally, $K(f)$ represents the isolation accomplished due to any structure (e.g. ground planes) and/or spacing between the two antennas.

A. Notation

According to the EPC Class 1 Gen 2 protocol, the RFID reader continuously transmits either amplitude modulated symbols or the carrier frequency, in order to supply the necessary energy to power-up the tags. A binary '0' is composed of a power-on interval, followed by a power-off interval of equal lengths. A binary '1' consists of a power-on interval of greater duration (1.5 to 2 times that of a binary '0') again followed

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by a power-off interval. Hence, an RFID-reader transmitted signal of amplitude A can be represented as:

$$x(t,f) = Ae^{j2\pi ft}I(t), \text{where } I(t) = \begin{cases} 1, & \text{power-on interval} \\ 0, & \text{power-off interval} \\ 1, & \text{carrier} \end{cases} \quad (1)$$

Therefore, a carrier frequency f is either transmitted or not. In the following notation, we assume that the input signal to the repeater is either voltage or current. Typically, antenna's and amplifier's gains are given in decibels (dB) of power ratios G^{dB}_{Power}. The corresponding voltage (or current) gain is:

$$\frac{y_{out}}{y_{in}} = \sqrt{10^{\frac{G^{dB}_{Power}}{10}}}, \quad (2)$$

All transfer functions of the closed loop model of Fig. 3 change with respect to frequency f. The time-dependence of each function is mapped in the appropriate phase-shift, which is of interest in the following analysis. Following the block diagram of Fig. 3, the following notation is defined:

- $G_{in}(f)e^{j\phi_{in}(f)}$ is the gain of antenna 1, where $\phi_{in}(f)$ is the phase shift of any signal at the output of antenna 1 with respect to frequency f.
- $H_F(f)e^{j\phi_F(f)}$ is the filter's transfer function, where again $\phi_F(f)$ is the phase shift due to the filter. The desired transfer function is defined next.
- $H_L(f)e^{j\phi_L(f)}$ is the RF limiter's transfer function, which again will be defined next.
- $G_{amp}(f)e^{j\phi_{amp}(f)}$ is the amplifier's transfer function.
- $G_{out}(f)e^{j\phi_{out}(f)}$ is the gain and phase shift of antenna 2.
- $G_{in\_c}(f)e^{j\phi_{in\_c}(f)}$ is the gain and phase shift of the part of the signal that is coupled back to antenna 1.
- $G_{out\_c}(f)e^{j\phi_{out\_c}(f)}$ is the gain and phase shift of the part of the signal that is coupled back from antenna 2.
- $e^{j\phi_K(f)}/K(f)$ is the isolation achieved due to any structure and spacing between the antennas.

B. Design

1) RF Limiter: The RF limiter should limit the input power in order to: i) protect the amplifier from the maximum allowable input power and ii) make sure that the radiated power of the entire structure never exceeds the maximum Effective Isotropic Radiated Power (EIRP) threshold, imposed by the standard. If the power at its input is below a given threshold P_{max}, its transfer function is 1; else, its transfer function is $P_{max}/P_{in}(f)$:

$$H_L(f) = \begin{cases} 1, & P_{in}(f) \le P_{max} \\ \frac{P_{max}}{P_{in}(f)}, & \text{else} \end{cases} \quad (3)$$

where $P_{in}(f)$ is the power at the input of the RF limiter. P_{max} will be defined in (16).

2) Closed Loop Analysis: The block of Fig. 3 can be simplified. The feedback path of the loop is represented by a single transfer function $H_B(f)e^{j\phi_B(f)}$, which is equal to the product of the three transfer functions of Fig. 3. Furthermore, let's consider that the input power at the limiter is less than

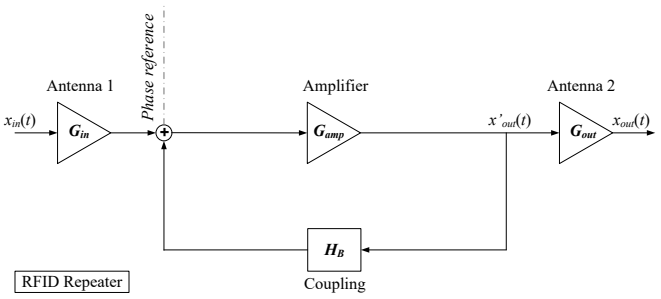

Fig. 4. Simplified block diagram of repeater.

P_{max} and that the bandpass filter perfectly filters all out-of-band emissions; i.e.

$$H_F(f) = \begin{cases} 1, & f \in BW \\ 0, & \text{else} \end{cases} \quad (4)$$

where BW is the desired operational bandwidth of the repeater, within given bands between 865MHz to 928MHz, depending on the bandwidth allocation for UHF RFID at the specific region. The actual filter-characteristic will be given in (14). Furthermore, assume that $\theta(f)$ is the entire phase shift in the forward path of the loop. The phase shift accounts for the transmission time within the medium (copper) plus any phase shift introduced by the amplifier, the filter and the limiter. Also consider that the "relative" phase is measured with respect (reference) to the phase of the incident field after antenna 1. The simplified closed loop model is represented in Fig. 4. The closed loop equation of the repeater is:

$$[x_{in}(t,f)G_{in}(f) + x'_{out}(t,f)H_B(f)e^{j\phi_B(f)}]G_{amp}(f)e^{j\theta(f)} = x'_{out}(t,f) \Rightarrow$$

$$\frac{x'_{out}(t,f)}{x_{in}(t,f)} = \frac{G_{in}(f)G_{amp}(f)e^{j\theta(f)}}{1-H_B(f)G_{amp}(f)e^{j(\phi_B(f)+\theta(f))}}. \quad (5)$$

The denominator of (5) is of great importance for the stability of the system. The following constraint must be satisfied in the design of the proposed amplifier:

$$\text{Constraint 1: } H_B(f)G_{amp}(f) < 1 \Rightarrow H_B(f) < \frac{1}{G_{amp}(f)}. \quad (6)$$

Constraint 1 states that decoupling must be greater than the forward gain of the amplifier. Otherwise, the output would continuously increase, saturating the amplifier. Defining $H_B(f)$ as:

$$H_B(f) = \frac{1}{C(f)}, \quad (7)$$

equation (6) can be rewritten as:

$$\text{Constraint 1: } C(f) > G_{amp}(f). \quad (8)$$

Equation (8) ensures that the amplifier is never saturated in the desired frequency band. Subtraction or addition of the output of the amplifier depends on the total phase of the denominator of (5). The actual gain of the closed loop is bounded by the

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two marginal values (for constructive and destructive phase-sum) defined in the following equation:

$$\frac{G_{in}(f)G_{amp}(f)}{1+H_B(f)G_{amp}(f)} \leq \frac{x'_{out}(t,f)}{x_{in}(t,f)} \leq \frac{G_{in}(f)G_{amp}(f)}{1-H_B(f)G_{amp}(f)}, \tag{9}$$

or by substituting (7):

$$G_{in}(f)\frac{G_{amp}(f)}{1+\frac{G_{amp}(f)}{C(f)}} \leq \frac{x'_{out}(t,f)}{x_{in}(t,f)} \leq G_{in}(f)\frac{G_{amp}(f)}{1-\frac{G_{amp}(f)}{C(f)}}, \tag{10}$$

The output of the repeater $x_{out}(t,f)$ is further amplified by the 2^{nd} antenna's gain $G_{out}(f)$, as demonstrated in Fig. 4. By replacing for $x'_{out}(t,f)$ in (5):

$$\frac{x_{out}(t,f)}{x_{in}(t,f)} = \frac{G_{in}(f)G_{amp}(f)G_{out}(f)e^{j(\theta(f)+\phi_{out}(f))}}{1-H_B(f)G_{amp}(f)e^{j(\phi_B(f)+\theta(f))}}. \tag{11}$$

By combining equations (9) and (11), one defines the maximum gain $G_{max}(f)$ of the repeater as:

$$G_{max}(f) = G_{in}(f)G_{out}(f)\frac{G_{amp}(f)}{1-\frac{G_{amp}(f)}{C(f)}}. \tag{12}$$

The power gain of the repeater is:

$$G_p(f) = \|\frac{x_{out}(t,f)}{x_{in}(t,f)}\|^2. \tag{13}$$

Now, one can define the necessary transfer function of the bandpass filter. An out-of-band signal must be sufficiently filtered out of the structure. Actually, the magnitude of the open loop gain, defined in (12), should remain smaller than 1 for out-of-band signals, i.e.:

$$\text{Constraint 2: } H_F(f)\begin{cases} =1, & f \in BW \\ \leq 1/G_{max}(f), & \text{else} \end{cases} \tag{14}$$

Equation (14) replaces the "perfect" filter assumed in (4). It makes sure that an out of band signal is significantly filtered out before it reaches the RF limiter (notice that the limiter is before the amplifier and the 2^{nd} antenna). One needs to set P_{max} in (3) to finalize the design. The output power must be kept below the maximum EIRP, therefore:

$$\begin{gathered} P_{in}(f)[G_{max}(f)/G_{in}(f)]^2 \leq EIRP \Rightarrow \\ P_{in}(f) \leq \frac{EIRP}{[G_{max}(f)/G_{in}(f)]^2}, \end{gathered} \tag{15}$$

where P_{in} is the input power at the limiter, defined in (3). The gains have been squared to account for power ratios, instead of voltage/current ratios that have been considered so far. The maximum gain of the repeater has been assumed. $G_{max}(f)$ is divided to $G_{in}(f)$, since $P_{in}(f)$ already includes the input-antenna gain. In addition, input power should be smaller than the maximum allowable input power of the amplifier P_{amp}. Therefore the limiter's power threshold should be:

$$\text{Constraint 3: } P_{max} = min\left\{ \frac{EIRP}{[G_{max}(f)/G_{in}(f)]^2}, P_{amp} \right\} \tag{16}$$

C. Expected Performance

Constraint 1 demands that coupling is smaller than the forward gain of the structure. It can be accomplished by introducing a ground plane between the two antennas and by spacing the antennas. Additional electromagnetic decoupling techniques can be applied, if the volume of the structure needs to be kept small. The phase (and hence summation or subtraction) of the feedback depends on the total length of the forward plus backward path of the structure and the phase-shift introduced by the amplifier. A low noise amplifier must be deployed, since the noise figure of the amplifier will affect the noise level at the reader. In addition, RF-clutter (multipath) may introduce unpredictable feedback, which is undesired. If the (amplified) multipath becomes stronger than the input, constraint 1 would fail and the system will be "rescued" from saturation only by constraint 3; i.e. the RF power limiter (at the expense of heating).

A good practice for the design of the repeater is to make sure that $C(f) >> G_{amp}(f)$. Under such assumption, from (10), the total gain of the structure becomes:

$$G(f) = G_{in}(f)G_{out}(f)G_{amp}(f). \tag{17}$$

III. Link Budget Analysis

A detailed link-budget analysis of different RFID configurations can be found in [24]. In the following paragraphs, only the affected parameters of the link-budget are considered, in order to investigate the effects of the proposed repeater.

1) Forward Path: Propagation from the reader to the tag (forward path) at distance R, is disrupted by the proposed repeater (Fig. 5). Assuming, far-field conditions, the power at the output of the repeater at distance x will be:

$$P_r^{in} = \frac{P_{read}G_{read}}{x^2}G_p\frac{\lambda^2}{(4\pi)^2}. \tag{18}$$

where P_{read}, G_{read} are the reader's transmission power and antenna gain respectively and G_p is the squared magnitude of the repeater's transfer function defined in (13). The amplified power at the tag becomes then:

$$P_t^{in} = \frac{P_r^{out}}{4\pi(R-x)^2}G_{tag}\frac{\lambda^2}{4\pi}, \tag{19}$$

where G_{tag} is the tag-antenna's gain. By substituting (18) in (19), one calculates the forward link budget:

$$P_t^{in} = \frac{P_{read}G_{read}G_{tag}}{x^2(R-x)^2}\frac{\lambda^4}{(4\pi)^4}G_p. \tag{20}$$

The corresponding power that reaches the tag directly from the reader at the same distance R is:

$$P_t^{direct} = \frac{P_{read}G_{read}G_{tag}}{R^2}\frac{\lambda^2}{(4\pi)^2}. \tag{21}$$

Calculating the ratio of the link-budget with and without the repeater, the power gain G_{power}^{tag} at the tag is:

$$G_{power}^{tag} = \frac{P_t^{in}}{P_t^{direct}} = \frac{R^2}{x^2(R-x)^2}\frac{\lambda^2}{(4\pi)^2}G_p. \tag{22}$$

Equation (22) reveals some important properties of the structure:

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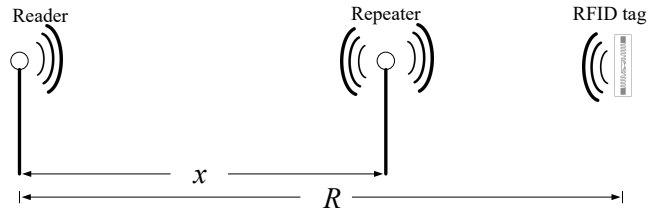

Fig. 5. The repeater is considered at a distance x from the reader.

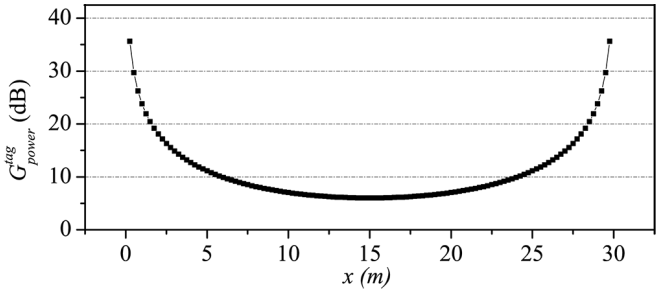

Fig. 6. Power gain at the tag vs. placement distance x.

- In contrast to wired communications/transmission lines, G^{tag}_{power} is not equal to the power gain of the repeater G_p. In fact, the power of the direct field at the tag could be greater than the "amplified" power of the repeater. The reason for this property is that the field is retransmitted at the repeater, thus attenuates at new spherical waves, originating from the repeater's output antenna.
- G^{tag}_{power} depends on the location of the repeater x with respect to the reader-tag distance R.

The necessary condition to ensure power gain at the tag is:

$$G^{tag}_{power} \geq 1 \Rightarrow G_p \geq \frac{x^2(R-x)^2(4\pi)^2}{R^2\lambda^2}. \quad (23)$$

By differentiating (22) with respect to $x \in (0, R)$, $G^{tag}_{power}(x)$ is minimized at $x = R/2$. The function is symmetrical around $x = R/2$. Therefore, greater G^{tag}_{power} is accomplished either by placing the repeater very close to the reader's antenna or very close to the tag. Eq. (22) is shown in Fig. 6 for R=30m, G_p=54.73dB and increasing placement distance x.

2) Repeaters in cascade: A reasonable case is to deploy repeaters in cascade such that the output transmitted power of the repeater equals the power originally transmitted by the reader. By substituting $P^{out}_r = P_{read}G_{read}$ in (18) and solve for the necessary repeater's gain we have:

$$G_p = (4\pi x/\lambda)^2 \quad (24)$$

Eq. (24) is plotted in Fig. 7. From (24), the designer can calculate the necessary gain to repeat the reader's transmitted power at a given distance. Eq. (24) can also be used to calculate the proper placement distance for a repeater with known gain. The delay introduced by each repeater will be in the order of ns; orders of magnitude smaller than 6.25μs, which is the shortest-bit-duration of the EPC Class 1 Gen2 protocol. Hence, the delay will not affect the timing of the protocol. When placing repeaters in cascade, the noise figure of the first amplifier is critical in achieving a very low overall

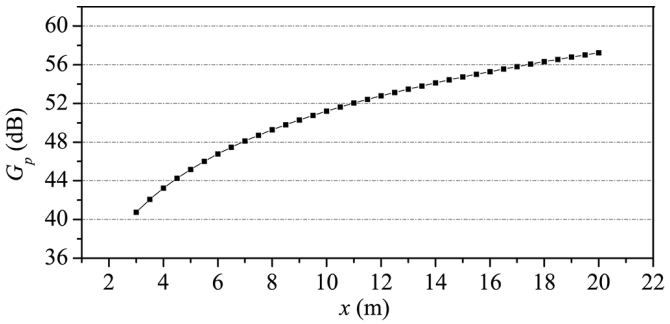

Fig. 7. Necessary repeater's gain vs. distance to repeat the reader's transmitted power.

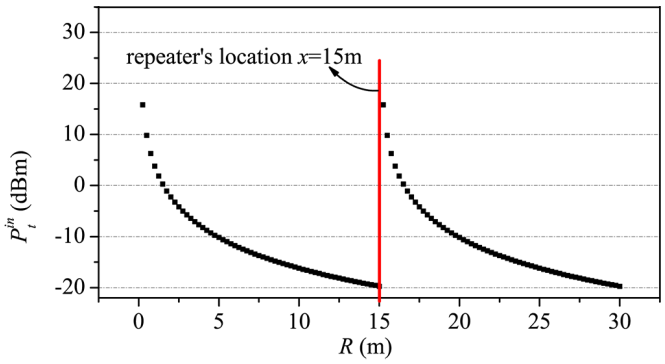

Fig. 8. Power at a tag for increasing distance from the reader, assuming a 54.73dB-gain repeater fixed at 15m.

noise figure. The total noise figure is not expected to surpass 2dB.

The power that reaches the tag at increasing distance from the reader is shown in Fig. 8; a 54.74dB repeater is considered at x=15m from the reader and $P_{read}G_{read}$=35dBm. Eq. 20 is used for $R > x$ (=15m, i.e. after the repeater) and 21 for $R \leq x$. By placing another 54.73dB repeater at 30m the power level that reaches the tag will again be repeated, as previously.

3) Round-trip link budget: By placing multiple repeaters, e.g. in series, or highly directional antennas, one can arbitrarily increase the forward-link gain of the system, thus providing any desired power at the tag. Then, successful identification of the tag depends on the tag-to-reader link.

The round-trip-link budget is analyzed for different cases (monostatic, bistatic, depolarization, fading effects, etc.) in prior art, e.g. [24]. For simplicity, in the following round-trip link budget formula, ϕ denotes direction of the next structure. For a monostatic case, the backscattered power that reaches the reader antenna P_b is:

$$P_b = \frac{P_{read}G_{read}(\phi_r)G_{tag}(\phi_r)G_{read}(\phi_t)G_{tag}(\phi_{read})G_p\lambda^6}{x_1^2x_2^2R^2(4\pi)^6}M \quad (25)$$

where, the distance terms are shown in Fig. 9, ϕ_r denotes the direction of the repeater, ϕ_t the direction of the tag and ϕ_{read} the direction of the reader's antenna; e.g. $G_{read}(\phi_r)$ is the reader's antenna gain towards the direction of the repeater. Similarly, gain G_p should be calculated accordingly, to include the gain of the input antenna of the repeater towards the reader and the output towards the tag. The term M is

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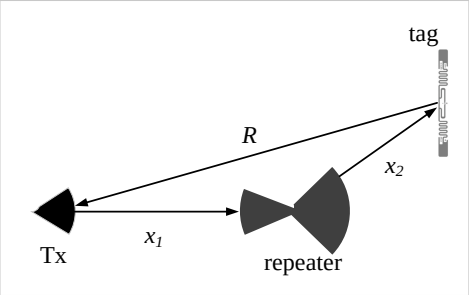

Fig. 9. Directions of propagation affect the gains of the antennas involved.

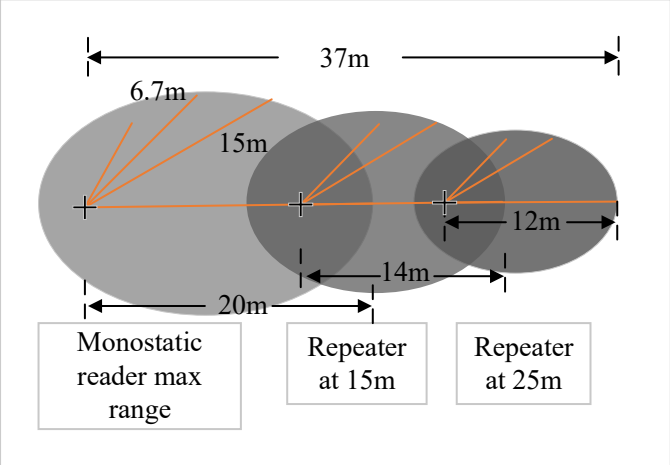

Fig. 10. Accomplished range with repeater is reduced, due to the sensitivity of the monostatic RFID reader.

given in [24] and represents the modulation factor, as the tag switches between two states. Equivalently the differential RCS term could be substituted [24]. Identification of the tag is accomplished if P_b is greater than the sensitivity of the reader.

To understand the importance of the reader's sensitivity, when multiple repeaters are installed, let's consider the following typical deployment strategy: A monostatic RFID reader with sensitivity at -85dBm transmits 30dBm from an 8dBic RFID antenna [25]. The maximum range for a tag with modulation factor M=0.1 and sensitivity -22.5dBm [21] is 20m. By placing a 54.7dB repeater at 15m, in order to retransmit 35dBm EIRP, the repeater's range is 14m (instead of 20m), achieving a new total range of 29m. The sensitivity of the reader limits the system's performance. By repeating the process as shown in Fig. 10, the range continues to shrink, as the backscattered power is smaller than the sensitivity of the reader.

By improving the sensitivity of the reader - possibly by dislocating the transmitter from the receiver – each repeater would double the range of the original monostatic configuration. Such performance assumes Line of Sight conditions for the tag-to-reader link. Therefore, one should consider deploying such a device depending on the environment. We are currently building the repeater, in order to deploy it in an exhibition area, where RFID tagged tickets will be monitored. Exhibits are located on the surrounding walls. Readers will be placed on the doors, separating discrete areas, while repeaters will illuminate the exhibition space. RFID tagged tickets will be identified by the reader, depending on the blockage of the path by the human body.

A similar application could be established on exterior parking lots, where the tags are typically located at the car's windshield and Line of Sight conditions can be established.

4) Maximum Range: The maximum range of the system will depend on the backward tag-to-reader link, as in typical wireless links. Let P_{tag}^{max} denote the maximum power backscattered by the tag and P_{sens} denote the minimum possible received power constrained by the reader's sensitivity. Then the maximum distance R_{max}, where a tag can be successfully identified, is given by:

$$R_{max} = \left(\frac{P_{tag}^{max} G_{tag} G_{read} \lambda^2}{(4\pi)^2 P_{sens}} \right)^{\frac{1}{2}} \quad (26)$$

The following remarks must be taken into account:

- Commercial tag's back-scattered power is not proportional to the incident power, due to the non-linearity of the charge-pump at the tag's front end [22]. Design is optimal for the minimum possible received power at the tag (sensitivity level).
- The maximum range depends on the reader's sensitivity P_{sens}.

The sensitivity of monostatic RFID readers is poor, due to the circulator at the reader [3], [23]. Best reported values for monostatic RFID readers are in the order of -85dBm. Furthermore, typical maximum tag's backscattered power is in the order of -20dBm to -30dBm, depending on the tag's chip. The tag's backscattered power also depends on the tag's antenna; its gain depends on its size and can be considered at best (for the larger tags) approximately 0dBi. Assuming a typical patch-antenna at the reader with gain between 4dBi to 7dBi, the maximum achievable range is in the order of 80m.

However, the thermal noise floor for a 1MHz UHF RFID channel is in the order of -110dBm. Therefore, typical front-end electronics would ensure a sensitivity level in the order of -95dBm for a bistatic RFID reader; i.e. when the receiver is different than the transmitter. Under such configuration current commercial passive RFID tags could be successfully identified by a maximum distance in the order of 350m, assuming a 7dBi gain of the reader's antenna.

IV. Measurements

A. Repeater's Gain

The "repeater" consists of two 8.3dBic antennas (5.3dBi per polarization axis) [25], facing opposite directions and a 37dB low-noise amplifier [26]. The limiter and the filter were not necessary, as the measurements were conducted in a controlled laboratory environment. Due to cable-losses, the amplifier's gain was measured 35dB. In agreement to the notation in 5-17, $G_{in}(f) = G_{out}(f) = 10^{(5.3/20)}$, $G_{amp}(f) = 10^{(35/20)}$. In order to calculate the achieved gain, one should measure the decoupling $C(f)$ between the two antennas. The corresponding setup is illustrated in Fig. 11.

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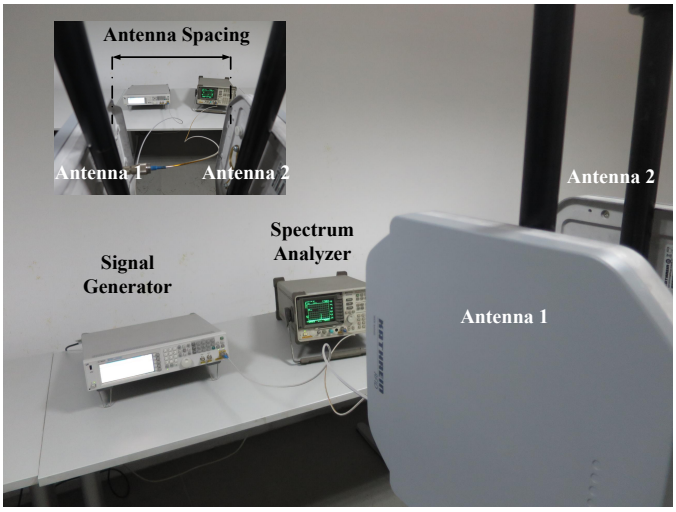

Fig. 11. Measurement of decoupling for increasing separation distance between antennas.

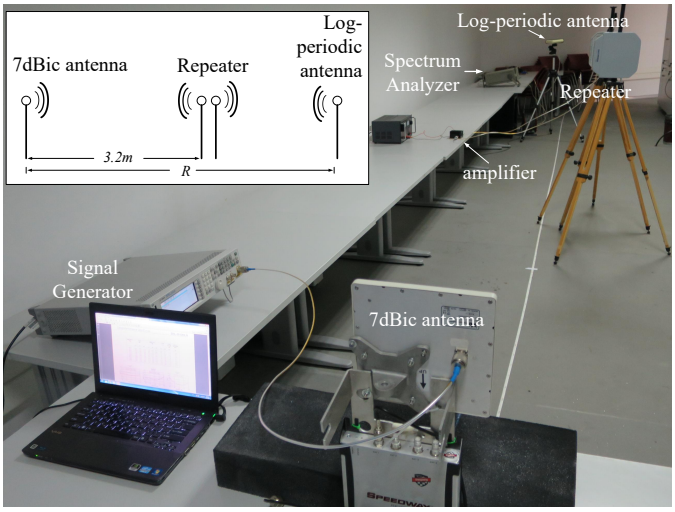

Fig. 12. Measurement of power gain at tag.

TABLE I
MEASURED DECOUPLING VS SPACING BETWEEN ANTENNAS

Distance (cm)	Decoupling $C^2(f)$ (dB)	Min Gain (dB)	Max Gain (dB)	Variability (dB)
25	45.5	46.3	51.6	5.4
41	47.5	46.75	50.95	4.2
71	47.5	46.75	50.95	4.2
82	52.5	47.5	49.8	2.3

The amplifier is disconnected. Antenna 2 (the output) is directly connected to the signal generator [27], while antenna 1 (the input) is connected to the spectrum analyzer [28]. The distance between the two antennas was gradually increased from 25cm to 82cm. The results are summarized in Table I. Decoupling $C_2(f)$ was increased from 45.5 dB up to 52.5 dB. Therefore, "Constraint 1", (8), was satisfied regardless of the spacing between the two antennas. By substituting in (10) and multiplying with the output antenna gain $G_{out}(f)$, one calculates the minimum and maximum power gain margins of the repeater. These are summarized in Table I. As the decoupling increases the corresponding variability reduces, approximating the limit for $C(f) >> G_{amp}(f)$, given in (17), which is: $10log_{10}G^2(f) = 48.6$ dB.

B. Measured Gain - Forward Path

Next the amplifier was connected between the two antennas, forming the UHF repeater at x=3m. The signal generator was connected to a 7dBic antenna [30] and the spectrum analyzer to a log periodic antenna. The signal generator transmits 20dBm at 865MHz. The received power is measured at several distances R, when the repeater is on and off, as shown in Fig. 12. The measured power gain agrees with the expected gain G^{tag}_{power} from (22), as illustrated in Fig. 13.

C. Tag Characterization - Effects on Repeater's Performance

The round-trip-link budget of (25) depends on M, which quantifies the ability of the tag to backscatter the incident power. The following set of measurements demonstrates the variation of M for different incident power levels.

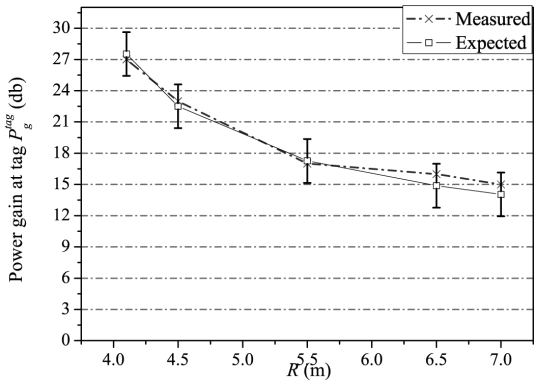

Fig. 13. Expected vs. measured gain at tag in dB. The max and min margins around each expected value are defined in (10).

A group of 4 tags was selected for measurements, with each one of them attached to a different IC: 1) Alien ALN-9740 "Squiggle" with "Higgs – 4" IC (-20.5dBm sensitivity), 2) Confidex "Survivor" with "NXP UCODE G2iM+" IC (-17.5dBm sensitivity), 3) Confidex "Carrier Pro" with "Impinj Monza 4QT" IC (-19.5dBm sensitivity) and 4) Tageos "EOS-400" with "Monza R6-P" (-22.1dBm sensitivity).

Each tag was originally set to a very small fixed distance from the "Speedway R420" [29] monostatic RFID reader (20cm). The transmitted power was gradually reduced from +30dBm to -10dBm at 1 dB step (at 866.9MHz). Since the reader allows for a 20dB total reduction (i.e. from +30dBm to +10dBm), each measurement was conducted in two phases: 1) with a 20dB attenuator connected to the reader's antenna and 2) without the 20dB attenuator connected to the antenna. The backscattered power at the reader's antenna in both cases was much higher than the reader's sensitivity for all measured cases.

- Each tag, stopped being identified at a different transmitted power level, as illustrated in Fig. 14. Both Squiggle and Confidex Carrier Pro were last identified at a reader-

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transmission power of 0dBm, while Tageos was identified for 4 dBm Tx power and Confidex Survivor for 8dBm Tx power. The necessary power depends both on the chip's sensitivity and the conjugate matching achieved between the antenna's complex impedance and the tag's IC at the "matching" modulation state. Those two tags that have achieved identification at the minimum transmission power are expected to have the best read-range, without the repeater; namely "Squiggle" and "Carrier Pro".

- The backscattered power measured at the reader for three of the tags' ICs (two from "Impinj" and one from "NXP") changes almost linearly with the transmitted power (increasing by 1dB every 2dB of increase of Tx power); a property which can be justified by the change of the equivalent load of the tag's front end (affected by the charge pump) with respect to the level of the incident power [31]. As the load changes, the antenna is mismatched to the tag's IC. In mathematical notation, M in (25) depends on the incident power at the tag, i.e. $M(P_t^{in})$ and decreases as P_t^{in} grows.
- The backscattered power from the Higgs 4 chip changes by only 3.5dB for a total of 30dB transmission power change. This could be explained by assuming a voltage regulator at the chip, which does not "drain" any more power than what is necessary for a specific "load". The same performance was verified by measuring more tags with the Higgs-4 IC.
- The maximum read-range with the repeater turned on, depends on the maximum power backscattered by the tag, P_{tag}^{max}, introduced in (26). From Fig. 14, P_{tag}^{max} is larger for Carrier Pro, Survivor and EOS-400, compared to Squiggle, due to the potential of those ICs to backscatter the strong available power. However, it is reminded that these power levels (-27dBm backscattered power!) were measured at 20cm-distance from the antenna, which is very small for warehouse-inventorying problems. Therefore, in typical problems, where the tag is expected to be at least 1m from the antenna, the incident power at the tag is expected to be smaller, hence the backscattered power will be smaller.

D. Range Measurements

Based on the maximum measured backscattered power by each tag, we can estimate the corresponding maximum possible read-range; it depends on the sensitivity of the reader. For example, consider the "Squiggle" RFID tag, measured in Fig. 14. By substituting -33dBm as the measured (maximum) reception power at the reader's 4dBi gain antenna, in the Friis Free-space equation for 0.2m Tx-Rx distance at 866.9MHz, one finds that the equivalent (maximum) power radiated by the tag is -20dBm. By substituting this transmission power for the minimum reader's sensitivity (-85dBm), one finds that the maximum expected range is 80m.

In order to verify the performance of the repeater, the read-range for each tag with and without the repeater was measured. All measurements were conducted outside in an open area, in order to avoid excessive multipath (expected in an indoor

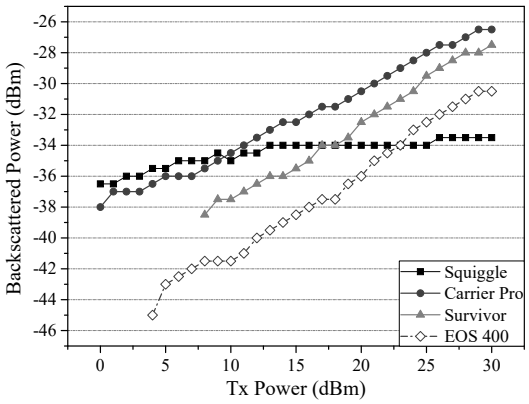

Fig. 14. Backscattered power at increasing transmission power for 4 different tags with different ICs at 20cm from the antenna.

Fig. 15. The reader's antenna illuminates an open area from an elevated position.

environment). Furthermore, the reader's antenna was elevated, to reduce the effect of ground reflection, as illustrated in Fig. 15. Each of the four tags was measured separately. The tag was moved at several locations, in order to avoid potential destructive interference field effects and the maximum range was recorded. The results are summarized in Table II, column 2.

Column 3 shows the maximum expected range, assuming that the repeater will deliver as much power as needed at the tag's circuitry to power up. This theoretical maximum range is calculated from the maximum measured backscattered power per tag, as illustrated in Fig. 14. The maximum range is bounded from the sensitivity of the receiver, assumed equal to -85dBm. As expected from the results of Fig. 14, Squiggle and Carrier Pro achieve the best (among the 4 tested tags) read range of 14m and 15m respectively. Then, the repeater was turned on and was placed at 25m, 35m and 50m from the reader's antenna. For every location, each of the four tags was separately measured, moving it at several distances around the

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TABLE II
ACHIEVED RANGE WITH AND WITHOUT THE REPEATER

Tag	Measured Range Without Repeater (m)	Maximum Expected Range with Repeater (m)	Repeater at 25m Measured Range after Repeater (m)	Repeater at 35m Measured Range after Repeater (m)	Repeater at 50m Measured Range after Repeater (m)	Repeater at 72m Measured Range after Repeater (m)
Squiggle	14	80	4	2.7	2	0.5
Carrier Pro	15	155	4	2.5	2	0.1
Survivor	8	135	1	0.5	0.5	0.1
EOS 400	8	95	3	2.5	2	-

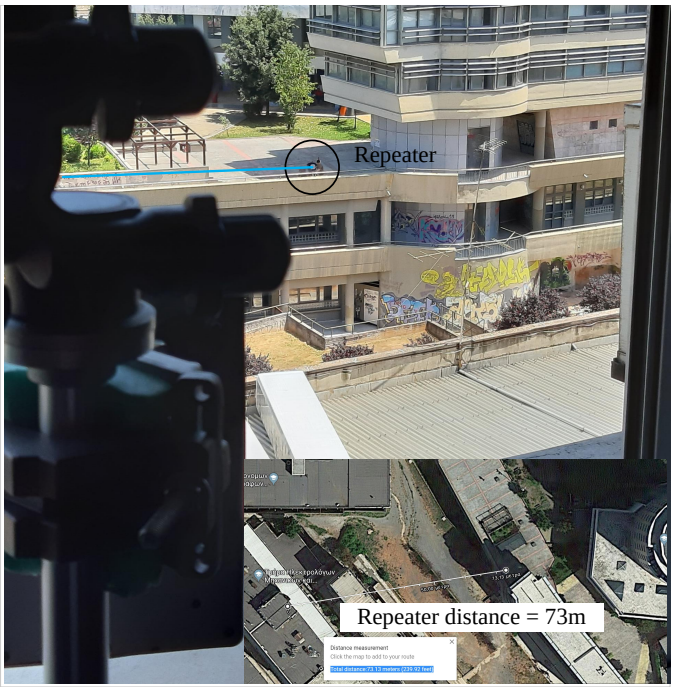

Fig. 16. Commercial passive RFID tags are identified from 73m distance.

repeater, finding the maximum read-range around the repeater (measured from the repeater) and verifying that the tag was successfully identified in agreement to the radiation pattern of the repeater's output antenna. For example at 25m reader-repeater distance, "Squiggle" was identified up to 4m from the repeater's position. As expected (Fig. 10) , as the reader-repeater distance grows, the corresponding repeater's range shrinks. The range of each tag after the repeater is also given in Table II. Since all tags under test were successfully identified at 50m (and there was no more "open" space), the measurements were conducted from one building to the next, reaching a reader-repeater horizontal distance of 72m, as illustrated in Fig. 16! At this distance, the EOS 400 was not identified. The other three passive RFID tags were identified in the vicinity of the repeater's output antenna as summarized in Table II.

V. CONCLUSION

State-of-the-art RFID ICs are designed for optimal performance at the limit of the chip's sensitivity (for incident power below -16dBm). This sets a bottleneck in the maximum expected performance of the proposed repeater, since the repeater (or a series of repeaters) can bring as much power as needed at the tag IC. Assuming the maximum transmitted power by the repeater will be 35dBm (equal to the maximum allowable EIRP by a reader antenna), a tag, 1m away from the repeater, will receive +4dBm power. A "matched" tag is expected to backscatter 10dB less power; i.e. in the order of -5dBm. Considering a bistatic-reader configuration to allow for better sensitivity, reader's sensitivity could be in the order of -95dBm; 15dB above the thermal noise floor of a 1MHz UHF RFID channel. Under such hardware modification, for a typical 7dBi reader-antenna, the read range of a ***batteryless*** RFID tag would be 2km!

With these in mind, passive RFID technology, will no longer be a short-range-only technology. Imagine, for instance that a network of environmental sensors could be installed above rooftop level (ensuring Line-Of-Sight conditions for the backscatter link) and be "interrogated" by a single reader and multiple repeaters, each installed in the proximity of a group of sensors. Passive RFID tags would represent the means to communicate sensor data back to the reader. Similarly, passive RFID-tagged containers could be interrogated from larger distances in a harbour.

Without any change in commercial RFID technology, the proposed repeater can be used to reduce the cost of any installation. The repeater's estimated cost is in the order of 100$. Instead of placing expensive readers every 10m, one can deploy multiple repeaters, up to a maximum distance of 50m. Evidently, the repeaters can be used in "cascade", such that any desired power will be available in greater distance. The total installation cost would reduce dramatically for larger areas, avoiding installation of multiple 2000$ RFID readers.

In conclusion, in this paper the possibility of using a UHF repeater has been analysed. The design, performance and limitations of the proposed repeater have been carefully considered. The proposed structure aims to increase the forward link budget in passive RFID technology, such that the tag's IC is successfully powered up at greater distances. Then, the sensitivity of the reader is exploited, in order to successfully interrogate distant tags. With current monostatic RFID technology and commercial tags, a range in the order of 80m can be accomplished; 73m-range was experimentally verified in this paper. The range is limited by the tag-IC's mismatch with the antenna at increasing power level, combined with the non-optimal sensitivity of monostatic RFID readers. By switching to bistatic RFID configurations - i.e. the transmitter is dislocated from the receiver - the improved sensitivity is expected to allow a new read-range in the order of 350m.

Finally, by changing the design of RFID-ICs, the expected range can be further increased.

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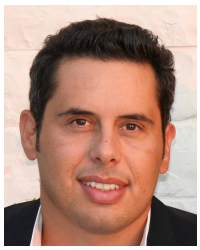

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He has participated in more than 20 research projects, 8 of which since 2007 as a principal investigator in the fields of Robotics, RFIDs, and Wireless Sensor Networks. He is currently the coordinator of project "RELIEF", where prototype robots and repeaters aim to ensure continuous inventorying and localization of RFID-tagged items at reduced cost. He was a Management Committee Member in the ICT COST Action IC301 "Wireless Power Transmission for Sustainable Electronics (WiPE)". He is the author or co-author of approximately 60 journal and conference papers.

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