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Interference Helps to Equalize the Read Range and Reduce False Positives of Passive RFID Tags

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***Abstract*—In various applications of RFID systems a reader should reliably get the ID of the tags that are within a bounded proximity region, termed the interrogation zone. This gives rise to two types of errors 1) False Negative Detections (FNDs), when tags within the intended interrogation zone cannot be read and 2) False Positive Detections (FPDs), when tags outside the zone can be read. The detuning effect experienced from the object a tag is attached to exacerbates the occurrence of FND. Solving FNDs by increasing the reader power increase the probability of FPDs for tags outside the zone. Hence, the design of an interrogation zone poses a trade-off between readability inside versus outside the desired zone. We present a novel method to reduce the probability of FNDs and FPDs, and practically equalize the achievable range for tags experiencing detuning. We propose to impose intentional interference on the communication between reader and tag. The expected effects of the proposed method are evaluated using experimental measurements. The results are positive, showing a sharp edge of the interrogation zone, and a strong equalization of the range of tuned and detuned tags. Hence it is concluded that by imposing interference enables design of well-defined interrogation zones for passive RFID systems.**

I. Introduction

Radio Frequency IDentification (RFID) has received great attention in recent years [1]–[3]. RFID is yet primarily utilized in supply chains, where the trend is moving towards item level tagging creating new challenges when deploying RFID systems.

As an example consider a store with item level UHF tagging. Readers are placed at the entrance, as illustrated on Fig. 1, in order to check that all items leaving the store have been paid for. The readers should therefore use sufficient transmission power, such that unpaid items tucked away in pockets and bags are read with high probability. Due to the high range when using high power, this may cause tags from the shelves inside the store to respond as well. This undesirable phenomenon is termed False Positive Detection (FPD).

In this paper we propose a novel method to create interrogation zones covering a confined area, e.g. just around the entrance of the store. By imposing interference while the reader is operating, tags still inside the store and outside the desired interrogation zone, are blocked from responding to the request from the reader. Moreover, tags experiencing detuning are equally affected by the interference. Hence, interference equalizes their read range towards the boundaries of the desired interrogation zone.

The mechanisms considered here are related to the concept of reader collisions, covering over two different types: Reader-tag and reader-reader collisions. The EPC Global Class 1 Gen 2 standard [4] implements a dense-reader-mode, allowing densely deployed readers to operate simultaneously in separate frequency bands. Modern readers are therefore able to filter out the undesired bands. Tags do not have this option, and are thus forced to cope with any interfering signal.

Immense work has been published in the area of reader collision already, proposing different methods to utilize the dense-reader-mode and optimize for low probability of reader collision. In [5], [6] the problem of reader collision is thoroughly described and existing methods to cope with this problem are surveyed. An example is [7], where reader collisions are described as a graph coloring problem, in order to derive a suitable reuse distance between the frequency channels. Alternatively [8] suggests using an algorithm similar to the Q-algorithm, from the Gen 2 standard, as MAC protocol for the network of readers. Most recently [9] proposes a method where readers are synchronized using a polling server, in order to avoid reader collisions. Moreover, [10] investigate what level of interference will cause a tag to not be identified by the reader. Additionally, different measures have been proposed to mitigate the problem of FPDs. In [11] two case studies are presented. They identify parameters in the physical setup of the RFID system in order to minimize false detections. In [12] a probabilistic model is utilized to filter the captured data, and in [13] two additional methods for data filtering are developed in order to avoid false detections. One method offering real-time filtering but with decreased precision compared to the second method, which is applying an offline data filtering. Though existing works present intelligent methods to avoid reader collisions, they are not differing between reader-reader collision and reader-tag collision. Moreover, the existing methods for reducing FPDs accept the presence of false detections and take measures to cope with them when they occur, rather than devising techniques for decreasing the probability of false detections in the first place. In [14] we investigated the potential of blocking tags from responding using interference, with positive results. In this paper we utilize this concept and present a novel idea using reader-tag collisions constructively to equalize the read range of tuned and detuned tags. In this way the probability of a FPD is reduced, making the interrogation zone a well-defined area. By imposing interference we

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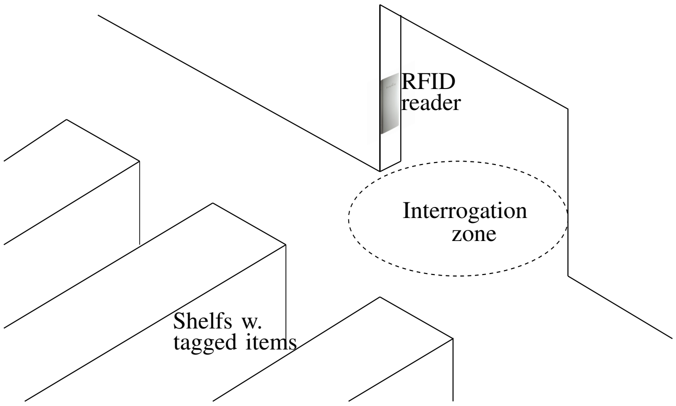

Fig. 1. A section of a store with item level tagging. The readers at the entrance should only identify items leaving the store area.

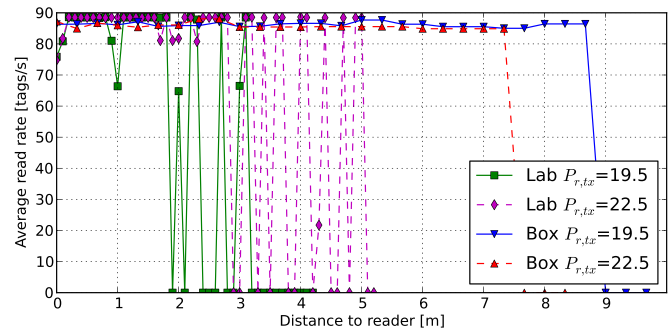

Fig. 2. The achievable range in an idealized environment compared to a multi path environment. Inside the shielded box the edge of the zone is given by a clean drop in rate, where the zone edge in the multi path environment has significant fluctuations. The power values are specified in dBm.

utilize some of the fundamental features of communication systems based on RF energy harvesting, as the interference is both an additional power source and a means to block tags from decoding the reader commands. The applicability of the proposed method is investigated through experimental evaluation and measurements.

The remainder of this paper is structured as follows: The motivation and proposed method are presented in Section II. Section III presents an analytical view on the interference-based mechanisms proposed in the paper. Section IV describes the experimental setup, and the results are presented in section V. In Section VI we discuss the findings and describe how the proposed method can be utilized and what effect it will have in a sample application. The final conclusions are drawn in section VII.

II. Motivation and Proposed Method

There is an inherent trade off between the read probability of tags inside the desired interrogation zone, and tags outside this zone giving rise to two types of reading errors. 1) False Negative Detections (FNDs), when a tag within the intended interrogation zone is not read and 2) FPDs, when a tag outside the intended zone is read. To ensure a high read probability anywhere in the interrogation zone, even for detuned tags, the reader should use a high interrogation power. This increases the probability of reading a tag outside the interrogation zone.

The concept of intentionally blocking tags is applicable whenever a low probability of both FPD and FND is required. For example applications requiring a well-defined zone with high read probability and sharply bounded, such that the read probability is low outside the zone. In order to block the tags that are not supposed to send reply, we adopt the principle of wireless jamming and impose interference on the communication between reader and tag. In [14] we investigated the potential of adopting this simple method in RFID systems, with promising results.

The background for [14] was that the reader and tag represents two different levels of complexity, and are thus expected to have different susceptibility to interference. Passive UHF tags are simple devices with two basic requirements in order to respond with their ID: 1) The power "in the air" from the reader signal must be above a certain threshold β and 2) the Signal to Noise Ratio (SNR) or Signal to Interference and Noise Ratio (SINR), denoted γ, must be sufficient for the tag to be able to decode the reader commands. In his book [15] Dobkin specifies $\beta = -10$ dBm, and this threshold is utilized throughout this work. It should be noted that with the evolution in tag circuitry since the publication of [15], β is today more likely to be less than -10 dBm. It has not been possible for the authors to find good references for which SINR requirement, γ, can be expected. But due to the simplicity of the tag, γ is expected to be fairly high, between $10-30$ dB, and variate with different tag types.

In [14] the impact of interference was investigated in an idealized environment inside a shielded box with absorbing material on all sides. In this work we reuse a large part of the setup, but move the measurement to a multi path fading lab environment. This setup is described in more detail in Section IV. As motivation we compare the achievable range in the idealized environment versus the multi path environment in Fig. 2, where the read rate is plotted as a function of distance to the reader antenna. Inside the shielded box, the distance was introduced using adjustable attenuators and an artificial propagation loss coefficient. Two interrogation powers were used, $P_{r,tx} = 22.5$ and $P_{r,tx} = 19.5$ dBm. The performance difference when moving to a more realistic environment is clear, especially at the edge of the interrogation zone where the good propagation conditions inside the shielded box enables a very sharp edge of the zone for both interrogation powers. In comparison the edge of the zone in the multi path environment shows severe fluctuations, making it difficult to talk about an actual zone edge. In fact, we can only define the reading range probabilistically. Clearly, such fluctuations are undesired. Depending on where the zone edge is defined within these fluctuations, their presence either decrease the probability of reading tags in certain positions inside the zone, FNDs, or increase the probability of reading tags outside the zone, FPDs.

The read rate is fluctuating between almost maximum rate and no replies at all. If the SNR requirement was not fulfilled we would expect to see some intermediate read rates as well, hence the problem at the zone edge is to power up the tag.

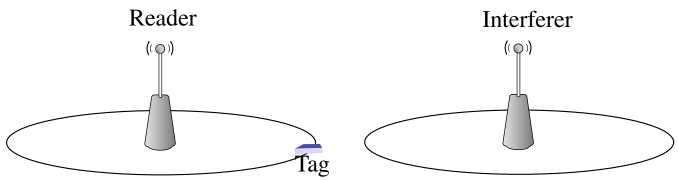

Fig. 3. The simplified scenario with a single reader and interference source, and tags located in between.

Ensuring sufficient power for the tags by increasing the interrogation power poses a trade-off. While it does increase the power received by tags inside the zone and with that the SNR, it also increases the SNR for tags outside the desired interrogation zone, which then increases the probability of FPDs. This effect is not desired, as the SNR requirement is already fulfilled, according to Fig. 2.

The same arguments goes for decreasing the interrogation power in order to decrease the probability of falsely reading tags outside the zone, i.e. the probability of FNDs increase especially if a tag is experiencing some level of detuning.

To mitigate the fluctuations at the zone edge we basically want to increase the power received by the tag, without increasing SNR. These are fundamental features of any communication system based on RF energy harvesting. By imposing interference the SNR is unaffected, while the SINR decreases. In this way the power requirement is fulfilled, while by controlling the level of interference we can control the SINR and thereby the range in which tags should be unable to interpret the requests from the reader.

The key point in this method is that interference will have the same effect on a detuned and a tuned tag located inside the interrogation zone. Hence by imposing intentional interference we expect to equalize the performance of tuned and detuned tags, and thus achieve similar read ranges. This means that if the size of the interrogation zone is controlled by adjusting the SINR instead of the interrogation power, the read range for different tags and objects is expected to be more coherent within an interrogation zone reading

III. Analytical Rationale

The scenario illustrated in Fig. 1 is an example of a real life application, where the proposed method is applicable. However, in order to evaluate the method theoretically, and later experimentally, we have chosen to further simplify the scenario. Instead of considering a store with multiple reader devices and a large tag population, we focus on a two device setup, a reader and an interference source, separated with some distance, as illustrated in Fig. 3. We then investigate how the interference affects the readability of a tag in the area between the two transmitters. In this way we have a simple scenario with only two devices, from which we can obtain the same effects as we would expect in the real life setup.

We utilize interference which is similar to the signal from an RFID reader, i.e. the signal is modulated and lies in the RFID frequency band, from $865 - 868$ MHz in Europe. This makes the concept of blocking tags similar to reader-tag collisions. To describe the rationale of this method and illustrate the expected effects, we use a simple analytical approach. The scenario is regarded as a case of diversity, where the powers from the reader and interferer are combined in the physical channel. The power received at the tag from the reader is given by the following model:

$$R_p = \mu_r \cdot |h_r|^2 \tag{1}$$

The wireless channel is assumed to be a multi path channel, i.e. the received signal amplitude is following a Rayleigh distribution. This means that the power of the received signal follows an exponential distribution, and $|h_r|^2$ is thus the channel coefficient modelled by an exponentially distributed random variable, with a mean value equal to 1. The Probability Density Function (PDF) of R_p is then given by

$$f(R_p) = \frac{1}{\mu_r} \cdot \exp\left(\frac{-R_p}{\mu_r}\right) \tag{2}$$

Where the mean power, μ_r, received from the reader at the tag is given by

$$\mu_r = P_{r,tx} \cdot t \cdot d_r^{-\alpha} \tag{3}$$

Where $P_{r,tx}$ is the reader interrogation power and t is the tag detuning coefficient. We consider detuning of a tag as a downscaling of its received mean power. Hence t can take on values in the interval from 0 to 1, where $t = 1$ represents a tuned tag, i.e. perfectly matched to the reader signal. The propagation loss factor is calculated from the distance to the reader, d_r, and the propagation loss coefficient, α.

The power received from the interferer, I_p, is modeled similar to R_p in (1), but instead of the index r, i is used to refer to the interferer parameters like transmission power, $P_{i,tx}$, distance to the interferer, d_i, etc.. The total power received at the tag, T_{rx}, is then given by

$$T_{rx} = R_p + I_p + N_0 \tag{4}$$

Where N_0 is the noise power. To power up a tag, T_{rx} must be above the threshold β. The ability to decode the commands from the reader then depends on the SNR or SINR. Without interference the SNR is given by

$$SNR = \frac{R_p}{N_0} \tag{5}$$

The noise floor is in general low, compared to R_p, hence the SNR is expected to be high. When interference is present the SINR is given by

$$SINR = \frac{R_p}{I_p + N_0} \approx \frac{R_p}{I_p} \tag{6}$$

Compared to I_p the power in the noise is small, and the SINR is thus reduced to the Signal to Interference Ratio (SIR).

In order to show the expected effect of the proposed method we have simulated an example using the parameters listed in Table I. The reader and interference source are separated by a distance of $d_{sep} = 10$ m. Using (1) and (3) randoms samples of the power from the reader and from the interferer have been obtained, and with (4) and (6) the total received power and

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	Notation	Value
Reader transmission power [dBm]	$P_{r,tx}$	22.5
Interferer transmission power [dBm]	$P_{i,tx}$	17
Channel coefficients [-]	$\|h_r\|^2$ and $\|h_i\|^2$	Exp(1)
Separation distance [m]	d_{sep}	10
Tuning coefficient [-]	t	$\{0.1; 1\}$
Path loss coefficient [-]	α	3

TABLE I
PARAMETERS USED IN THE EXAMPLE PLOTTED IN FIG. 4.

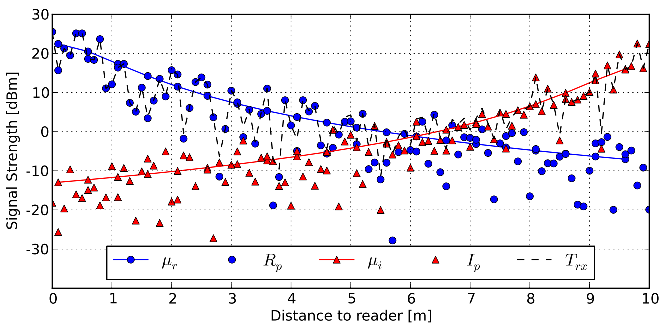

Fig. 4. The simulated power from the reader and interferer respectively, received at a tag with an antenna tuned to the correct frequency. The received power is plotted as a function of the distance to the reader antenna. The mean power is plotted as a solid line with samples of the fast fading instantaneous power distributed around it.

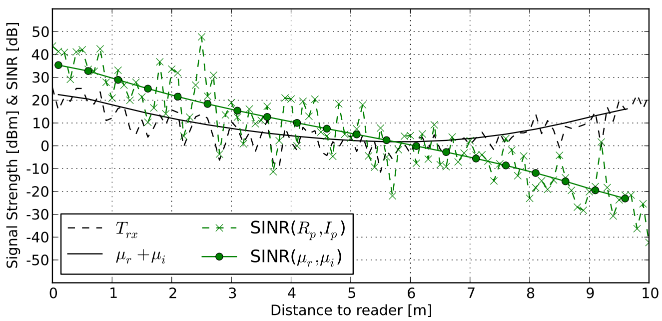

Fig. 5. The simulated SINR and the total power received by the tag, i.e. the sum of the instantaneous power from reader and interferer, plotted as a function of distance to the reader antenna.

SINR have been calculated and are plotted as a function of the distance to the reader in Fig. 4. Initially we consider the power received with a tuned tag, and Fig. 4 shows the Received Signal Strength (RSS) from the reader and interferer at the tag respectively, in positions between the two sources. The solid lines represent the mean power and we see the exponentially distributed samples of instantaneous power distributed around those mean values. For a small distance to the reader the T_{rx} is dominated by the interrogation signal, and vice versa when the tag is close to the interferer. In intermediate distances to the reader, the faded samples of the reader signal tends to fall below -10 dBm, and thus failing to fulfill the power requirement to power up the tag. However, due to the contribution from the imposed interference the received power at the tag lies above, or very close to, -10 dBm, ensuring that there is enough power available "in the air". Moreover, when the two signal components are comparable in size, summing them up evens out the fast fading effect, which is a well known diversity

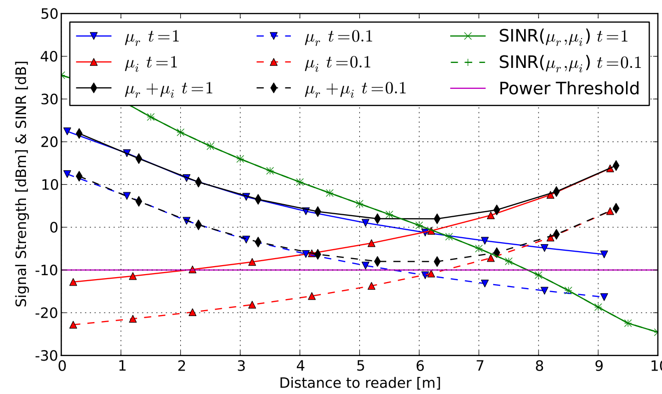

Fig. 6. The simulated mean power received by a tuned and a detuned tag respectively, and the resulting SINRs.

effect.

In this simulation the trend of the SINR is monotonously decreasing, as can be seen in Fig. 5. With the received power above the threshold, the question of whether the tag can reply purely depends on the SINR threshold, i.e. the level of SINR where the tag is no longer able to decode the signal from the reader.

In addition to enable blocking of tags, Fig. 4 shows another feature of the proposed method. When the mean power is just above the threshold multi path effects will have the instantaneous RSS fall below the power threshold. In the same way multi path effect will make the RSS jump above the threshold when the mean power is just below the threshold, albeit this effect is not directly visible on Fig. 4. In effect the range of a reader, or the edge of an interrogation zone, becomes a diffuse concept in the normal case, which corresponds to the graphs in Fig. 2. However, by imposing interference and thereby fulfilling the power requirement, the range of the reader only depends on the SINR. Clearly the SINR is also expected to fluctuate with the multi path fading, given Fig. 5, but the resulting variations at the interrogation zone edge are expected to decrease. This enables sharper defined interrogation zones when adding interference.

When comparing the readability of a tuned tag with that of a detuned tag, the interference has a significant impact. In order to reduce clutter in the graph, only the mean powers have been plotted in Fig. 6, as they are sufficient to show the overall trend. The solid lines in Fig. 6 represent the tuned tag and are just repeated from Fig. 4, where the dashed lines represent a detuned tag with $t = 0.1$. This means that the tag is receiving 10 dB less power from either of the sources. Hence the plots for interrogation power, interference power and their sum are shifted 10 dB. Focusing on the interrogation power in the absence of interference, the mean power falls below the -10 dBm threshold around 5.5 m where the range of a tuned tag is beyond the 10 m. The span of the interrogation zone is thus depending on the object material and how it detunes the tag.

Adding interference ensures that the total received mean power does not drop below the power threshold between the

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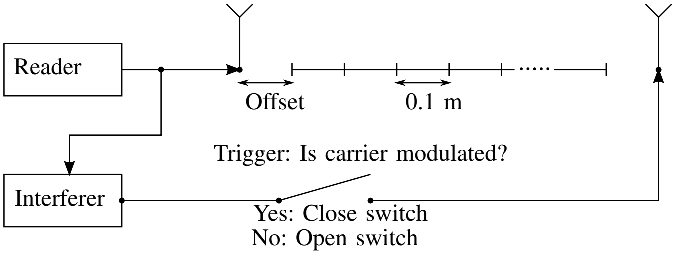


Fig. 7. A block diagram showing the experimental setup. The reader commands triggers the interferer, leaving tag responses undistorted.

reader and the interference source, and the readability therefore solely depends on the SINR. The detuning of a tag affects both the reception of the reader and the interference signal, hence the mean value of the SINR for a detuned tag will be the same as for a tuned tag. It should be noted that due to multi path effects the instantaneous SINR values are not the same, but they follow the same mean. This means that by introducing interference we can equalize the readability of tuned and detuned tags creating a more uniform interrogation zone.

IV. The Experimental Setup

The simplified setup, using a single reader and interferer, presented in section III is utilized in the experimental evaluation as well. When imposing interference we are artificially creating reader collisions, where both Co-Channel Interference (CCI) and Adjacent-Channel Interference (ACI) are utilized. The tag is a simple device without the usual filters in the receiver to filter out undesired bands. Both interference types can thus contribute with power to the tag, and are expected to disturb the tags ability to decode reader commands. In this work we focus on reader-tag collisions as the target is to create a sharp edge of the interrogation zone, and therefore ensure that a tag outside the zone is not replying to queries from the reader. Measurering if the tag responds by connecting a probe directly on the tag would change the electromagnetic characteristics and the reception parameters of the tag significantly [16]. Hence we partly reuse the setup from [14], where only the reader commands are interfered, leaving tag responses unaffected by the interference. Due to the high sensitivity of the reader compared to the tag, it can be assumed that when no tag reply is detected, the tag was unable to interpret the reader commands. This way of interfering is complex and only required since we need to know if the tag was blocked. In a real life setup, a simple interferer transmitting during both reader and tag transmissions could be utilized.

In contrast to the results in [14], this work considers the experimental evaluation in a multi path environment. A block diagram illustrating the utilized setup is shown in Fig. 7. The tag is mounted on a motorized slide, that moves the tag between the two antennas. The slide has a range of 1.2 m, and when larger distances are required the offset is changed by moving the reader antenna further away. A detailed description of the utilized equipment and measurement procedure can be found in Appendix A.

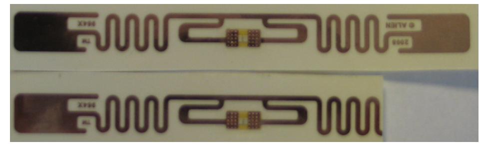


Fig. 8. A tuned tag along with a tag detuned by reducing the antenna dimension.

When an RFID tag is attached to an object, the antenna is detuned as its antenna characteristics are affected by the object material. For a reflective material the impedance of the antenna conductor changes significantly compared to when the antenna is in free space. Non-reflective materials alter the wavelength of the incoming signal due to the dielectric constant of the material. Further details on how the reflective and dielectric abilities of the object affects the tag antenna is outside the scope of this paper. Basically the input impedance of the antenna change which introduces a matching loss that decreases the reception capabilities of the tag. A matching loss means that the tag receives less power, i.e. t decreases.

In the experimental setup utilized in this work it is not viable to detune the tag by attaching it to an object. Instead we directly alter the antenna dimensions by removing parts of the conductor. Fig. 8 shows the two Alien Squiggle tags utilized in our experiments: One full tag and one where approximately 25 % of the antenna has been removed. Reducing the conductor dimensions increases the resonance frequency. This increases the input impedance at the incoming frequency in the interrogation signal, and introduces a matching loss similarly to when the tag is attached to an object. It is not possible to specify the exact value of t as it would require to measure directly on the tag. Instead we denote the detuned tag by $t < 1$ when plotting the measurement results.

The resulting setup is illustrated in Fig. 9, together with the lab environment, where the experimental evaluation was conducted. This is a normal indoor environment with reflecting surfaces like tables, cabinets and various lab equipment. The performance will therefore suffer from multi path fading, representing a real life setup.

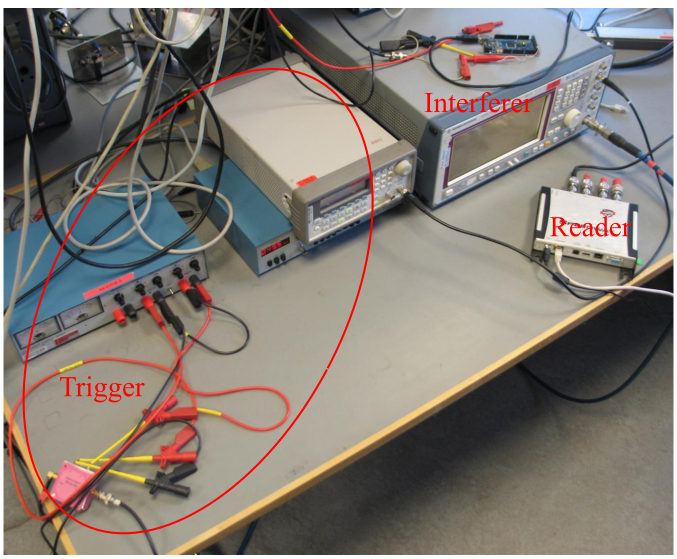
V. Results

In order to show how tags can be blocked, and how it is possible to design sharply defined interrogation zones a set of experiments have been conducted. Each test serves an individual purpose and shows different aspects of our findings.

A. Interference Type

The key concept in this work is to impose interference as an additional power source for the tags and to enable control of the read range by adjusting the interference power. In this way tags outside the desired zone are blocked from responding due to the interference. Due to the relatively wide frequency range of the receiver in the tag both CCI and ACI are expected to contribute with power and enable blocking of tags when the SINR gets sufficiently low. However, as we are interested in a well-defined interrogation zone with a sharp

(a) The reader and interferer antennas with the tag in between.



(b) The reader and interferer equipment.

Fig. 9. The experimental setup in an indoor lab environment.

edge we investigate the impact of ACI and CCI respectively. CCI uses the same center frequency as the reader, 865.7 MHz, where ACI uses the center frequency of the adjacent channel, 866.3 MHz. In order to show the generality of the results, we use two combinations of powers: Interrogation power of 22.5 dBm with 17 dBm interference and an interrogation power of 27.5 dBm with 20 dBm interference, and the resulting ranges are plotted in Fig. 10. The rate has some fluctuations due to the multi path environment, but here we see the expected intermediate read rates when the range is limited by SINR over power "in the air". The fluctuations vary with the position on the slider, hence not all curves has the same fluctuations as the rate goes to zero. But the general trend is clear, and judging from the resulting range, CCI is the most harmful interference type of the two. However, what is more interesting is how the read rates decay with distance to the interrogating reader. Compared to CCI, ACI has a steep slope making the rate drop from maximum to around zero within a

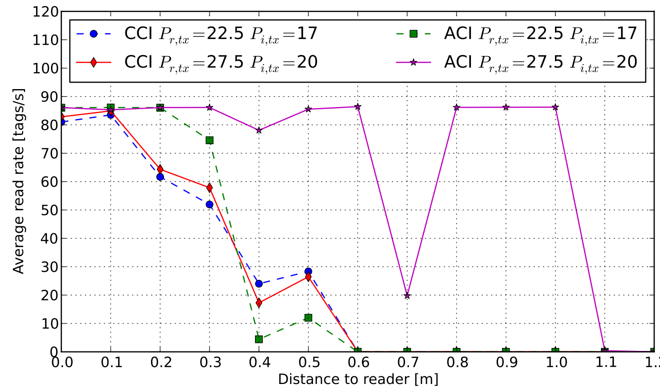


Fig. 10. The read rate plotted as a function of distance, when affected by CCI and ACI respectively. The power values are specified in dBm.

0.2 m change in distance, where it takes CCI 0.5 m to make a similar drop. ACI is thus better suited for creating a sharp edge of the interrogation zone and block tags from responding outside the zone. Hence only ACI is utilized in the subsequent experiments.

B. Resulting Range

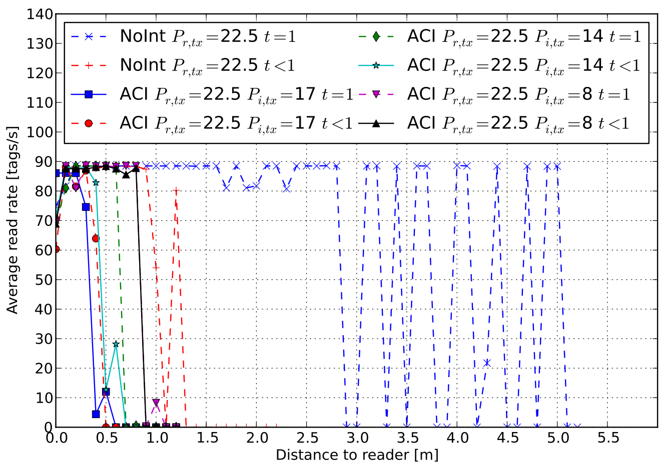
This experiment is conducted using a single interrogation power, 22.5 dBm, and three interference powers, 17, 14 and 8 dBm. The resulting ranges are plotted in Fig. 11. When interference is absent we see the expected range difference between a tuned and detuned tag, in this case around 4 m. This shows that a detuned tag require more power "in the air" to be able to respond, hence in case of detuned tags, the probability of FND is larger compared to tuned tags. Near the zone edge we see rate fluctuates similar to those plotted in Fig. 2.

The range is significantly reduced when interference is added, and Fig. 11(b) shows a close up of these graphs. Decreasing the interference power is equivalent to increasing the SINR, hence it is expected that the achievable range under interference increase for decreasing interference power.

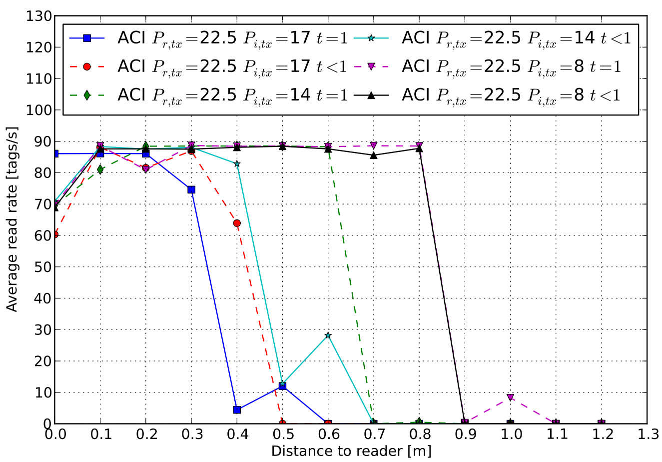
Considering the difference in range between a tuned and a detuned tag under a certain interference power, we see they are only differing with up to 0.2 m. Moreover, the edge of the interrogation zone is free of fluctuations and appear sharp and well-defined. This corresponds to the expectations explained in Section III.

C. Reaching a Specific Range

When designing interrogation zones, a certain range is often desired. Hence in continuation of Section V-B we show how both tuned and detuned tags can meet a certain range under the influence of interference. As an example we target an interrogation zone that spans 1 m from the reader antenna. For the case without interference we adjust the interrogation power to fit the read range of a tuned tag. Investigations showed that an interrogation power of 12 dBm was a good match to the desired range. The objective is then to see if the same range can be reached with a combination of a higher interrogation power and interference. In this case the reader interrogates



(a) Read rate with and without interference.



(b) Closeup of Fig. 11(a) repeating the plots of the read rate when interference is introduced.

Fig. 11. The read range of a tuned and detuned tag respectively. The introduced interference ensures that the read range of tags with different antenna characteristics will be approximately equal. The power values are specified in dBm.

with 22.5 dBm, and in order to meet the range of the tuned tag, two interference powers have been utilized, 5 and 8 dBm. In Fig. 12 the resulting read ranges are plotted. As expected, the read ranges of a detuned and a tuned tag appear very different in the absence of interference. The read range of the tuned tag is around 1 m, and only about 0.1 m for the detuned tag, which corresponds to decrease in range of ~ 90 % in this parcular setup.

When imposing interference we see that a detuned and a tuned tag have similar range, that lies close to that of the tuned tag without interference. In fact, with an interference power of 5 dBm, we get a range of 1 m for the tuned tag and approximately 0.9 m for the detuned tag, i.e. similar range as the tuned tag without interference.

The largest difference observed in this setup up, between the range of tuned and detuned tags under interference is 0.1 m, when the interference power is 8 dBm. This corresponds to a reduction of 10 % in range when using a detuned tag over a tuned tag. This reduction is significantly less compared

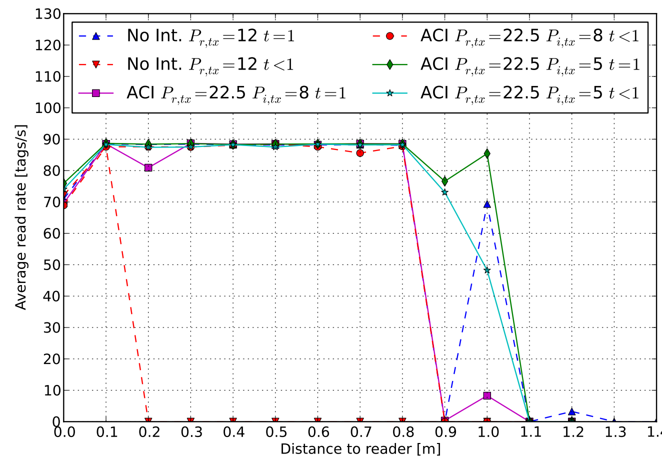


Fig. 12. The read range of a tuned and detuned tag respectively, when a read range of approximately 1 m is desired. The power values are specified in dBm.

to the difference without interference. Hence by imposing interference, the range of the tags are more equalized.

VI. System Level Implications

In this work we have proposed an idea that equalize read range and with that enable the design of sharply defined interrogation zones. Through experiments we have shown that the concept works at the link level when interference in is imposed on the communication between a reader and a single tag. In this section we discuss the implications of implementing the proposed concept in an RFID system in a more realistic scenario. As an example consider the RFID system illustrated in Fig. 13 covering the floor of a store or a factory.

In order to obtain a good coverage multiple readers have been utilized, denoted R_1 to R_6, each covering a separate section of the floor. In this application coverage, readability and location are the main concerns, in particular this means the RFID system should cover as much as possible of the floor, and a tag should be identified with ~ 100 % probability. Additionally it is desired to be able to locate a tag based on the reader who reads. The distance separating readers poses a trade off. In principle a distance twice the longest possible read range should be utilized, i.e. the read range of a tag in free space or at least the read range of a tag attached to the least RF obstructive object in the application. If a lower separation is used the probability of FPDs increase, making the location of the tag ubiquitous. A larger reader separation will however create so-called black spots between the interrogation zones, i.e. areas where tags are read only with low probability. Moreover, from Fig. 2 we have that the range of an RFID tag in a multi path fading environment is probabilistic and depends on the level of detuning of the tag, i.e. which object it is attached to, as it affects the tags ability to harvest energy. This is illustrated in Fig. 13 where each interrogation zone is encircled by a grey scaled belt and the width of this belt represents the interval of the actual read range of the tags. The interference range of a wireless link is known to be larger than

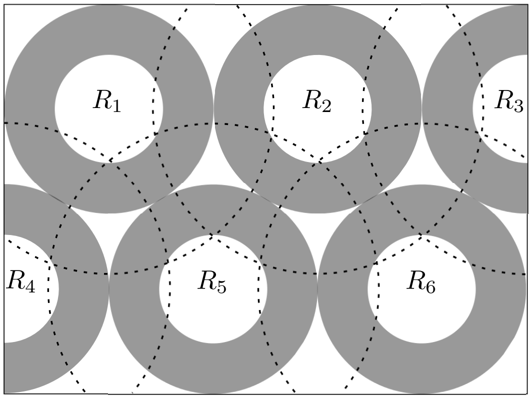


Fig. 13. Rectangular factory floor covered by an RFID system with multiple readers, R_1 through R_6. The width of the grey scaled belt encircling each interrogation zone represents the interval in which the read range lies of tags experiencing different levels of detuning. The dashed circle marks the interference range of each reader.

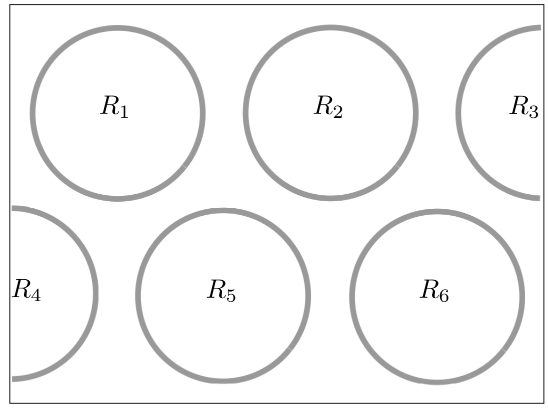


Fig. 14. Rectangular factory floor covered by an RFID system with multiple readers, R_1 through R_6. By embracing the interference between the readers the read ranges of tags are equalized, and the interrogation zones are now bounded by a sharp edge compared to Fig. 13.

the communication range, and in this case it is illustrated by the dashed circle around each reader in Fig. 13. This gives rise to the two types of reader collisions:

Reader-reader collision: Normally these collisions are avoided using frequency diversity and assigning different frequency channels to adjacent readers, and in some cases utilize a method for dynamically hopping between channels.

Reader-tag collision: Tags are simple transceivers without internal filters to filter out undesired frequency bands, which potentially will render a tag unable to decode any of the reader signals. The only way to completely avoid these collisions is to restrict readers from interrogating simultaneously.

By embracing the interference between readers, instead of trying to avoid it, we are constructively utilizing the large interference range and the resulting reader-tag collisions in order to block tags from responding. This allows for continuous reading and we have thus no loss of coverage and spatial reuse. The results presented in this work show how the read ranges are equalized for tags experiencing different levels of detuning. The achievable read range decrease due to the interference, but the coverage of a reader becomes more deterministic as illustrated in Fig. 14, where the grey scaled belt have been reduced to a thin line. In order to show the applicability of the proposed concept asynchronous interrogation and interference powers have been applied in this work. This is not desired in an application like the one illustrated in Figs. 13 and 14. However, identifying the optimal combination of interference power and interrogation power is an optimization problem and outside the scope of this work. In fact, by showing, with this work, that the proposed concept can be used to equalize the read range and enable sharply defined interrogation zones, leaves an interesting problem to be investigated in future works: *How to cover a maximal percentage of the floor with N readers, provided that the probabilities of experiencing FPDs and FNDs are within specified limits?* This introduces several optimization issues, e.g. how to calibrate the optimal power combination for a given environment and reader positions. Moreover, an algorithm is required for implementing the optimal hopping in frequency for the readers, as the impact of the interference at the tag will decrease with frequency distance. However, these are optimization issues which is outside the scope of this work, and what is optimal will vary with equipment, environments and applications.

VII. Conclusion

In this paper we propose a novel way of utilizing interference constructively in Radio Frequency IDentification (RFID) systems. Our focus is twofold: 1) The combination of a large propagation loss and fading from a multi path environment creates very diffuse zone edges. This results in high uncertainty of reading a tag located close to the edge of an interrogation zone. 2) The fact that the achievable read range of a tag decreases with the level of detuning of its antenna. These aspects increase the probability of both False Negative Detections (FNDs) and False Positive Detections (FPDs), and are related to the power required to energize the tag

We propose to introduce interference intentionally, in order to ensure that sufficient power is available "in the air" and block tags outside the desired interrogation zone. The interference introduces artificial reader-tag collisions and decreases the Signal to Interference and Noise Ratio (SINR). Tuned and detuned tags are experiencing the same SINR, thus their read range are equalized. Moreover, by controlling the interference power, and hereby adjust the SINR, we can control the range of the interrogation zone. Outside the zone, SINR is too low and tags are blocked from responding since they are unable to interpret the reader commands.

These expected effects are described through an analytical background and validated through experiments and measurements. With respect to blocking tags from responding Co-Channel Interference (CCI) showed most harmful. But Adjacent-Channel Interference (ACI) gave the steepest roll-off in read rate, hence this type of interference was used in all subsequent evaluation. The results show that the range of tuned and detuned tags are equalized. A difference in read range

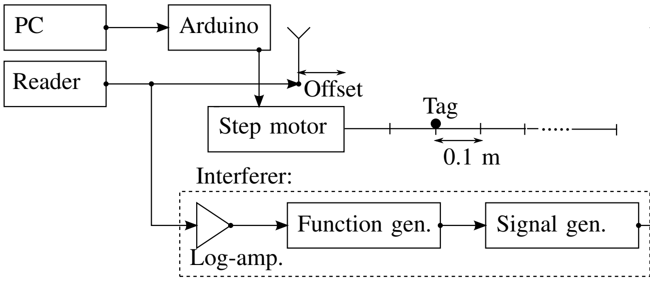


Fig. 15. A block diagram showing experimental setup in details.

is still possible, but our results show that it is significantly smaller compared to the difference without interference, i.e. the probability of FNDs is kept low. Additionally the zone edges show only small fluctuations, resulting in a low probability of FPDs. Thus by imposing interference we enable the design of well-defined and sharply edged interrogation zones.

For future work it is desired to further investigate how to calibrate the level of interference required to obtain the desired interrogation zone, as this will depend on the environment and the material of the tagged objects. Moreover, extending this method to a multi reader setup would be an interesting extension to this work.

Appendix A
Detailed Measurement Procedure

In Section IV a brief overview is given of the experimental setup. However the details of this setup is illustrated in Fig. 15. A PC is used to synchronize the interrogation process and the movement of the tag. This is done through a small Java program alternating between interrogating and moving the tag. The tag, an Alien Squiggle [17], is attached to a motorized slide and to operate the slide we use an Arduino board controlled through the Java program. To control the interrogation process the Java program uploads the reader specifications to the reader, initiates the interrogation and terminates it again after the desired duration of a reading period.

In this setup it is only desired to interfere the readers transmission in order to isolate the impact of the interference to the tags ability to decode the reader signal. Hence the interferer is triggered when the reader transmits information in addition to the constant carrier wave transmitted by the reader. This is realized using a logarithmic amplifier identifying any modulation of the carrier wave. The output of the amplifier is not sufficient to trigger the signal generator creating the interference signal, hence the amplifier triggers a function generator that generates a proper square wave to trigger the signal generator. Table II lists the equipment and various settings used to realize this setup. The measurements are then conducted by letting the tag traverse the distance from the reader antenna to the interferer antenna in steps of 0.1 m. For each tag position the reader interrogates for a period of 12 s, and with a read rate around 90 tags/s this gives approximately 10^3 samples of the tag response. The average read rate is then calculated over the 12 s reading period for each tag position.

Equipment:	
Reader	Impinj Speedway Revolution
Interferer	Rohde & Schwarz Signal Generator SMP22
Amplifier	Logarithmic amplifier AD8307
Function generator	Agilent Function Generator 33250A
Micro controller	Arduino Mega
Tag	Alien "Squiggle" ALN9640
Settings:	
Dense reader mode	Yes
Tag data encoding	Miller-4
Tag population	1
Reading period	12 s
Step size	0.1 m
Interference modulation	BASK, 80 kbps

TABLE II
Equipment utilized in the experimental setup.

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Kim Olesen was born in 1962. He received the M.Sc. E. E. degree from Aalborg University in 1988. He has been employed in industry until 1994 where he was employed by Aalborg University, Center for Person Kommunikation, CPK and has been with Aalborg University since, now as the head of all laboratories at the Department of IKT. His main contributions has been building several generations of Aalborg Universitys channel sounding systems and conducted numerous measurement campaigns. The latest channel sounder is a true parallel MIMO sounder with 16 transmitters and 8 receivers which can be distributed and on different frequencies.