Assessment of the Physical Interface of UHF Passive Tags for Localization

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Abstract - **This paper looks into the possibilities for localization of RFID tags, within the interrogator read field, using native technology features. As there are several standards, essentially different in the underlying physical principles, only passive UHF tags, compliant with ISO18000-6/GEN2 are considered.**

Considering the established communication format, first a simple reader array is proposed, implementing activation separation. The array is simulated to optimize performance.Then an experimental set-up is built to assess the suggested, antenna configuration. The results from this activation field tests, are compared with a typical commercial implementation.

A channel sounder is then used to measure the responses of the two antenna arrays, using an actual tag antenna, with the chip removed. Most typical situations are considered, including deterministic shape objects and random shape objects, as well as different tag positions and polarizations.

Finally a simple signal processing algorithm, that determines the positions of passing tags, is applied to the measured data. An order of wavelength accuracy is achieved.

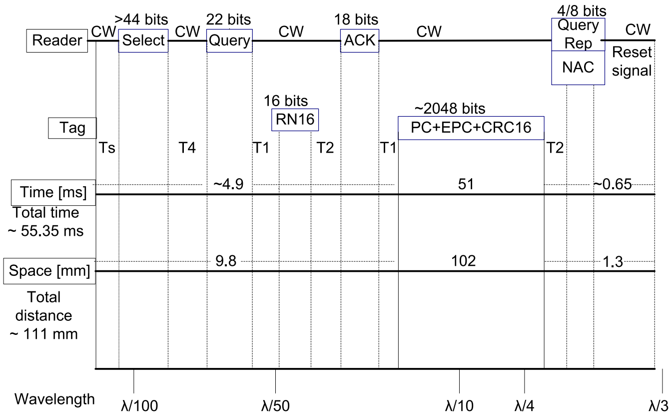

FIGURE 1 - SINGLE TAG COMMUNICATION TIMING (FOR DEFINITIONS REFER TO [3])

I. INTRODUCTION

RFID technology is steadily replacing BAR codes in most applications requiring object identification. One major advantage is the dropped clear line of sight requirement for identification. When it comes to industrial applications, passive UHF tags are the preferred choice, having a number of advantages over lower frequency tags, range and memory capacity being among the most important. Their popularity is constantly growing as more and more companies and government agencies demand an end to end supply chain monitoring [1].

The lack of line of sight however, can also be seen as a drawback since it leaves some ambiguity regarding the location of the replying tag. Despite that, so far most efforts have been focused on the mere reading of the tags. RFID antennas, along with the reader, are usually placed in a way that maximizes the probability of a valid read.

Precise localization on the other hand, can be crucial for many applications. Typically a reader would be able to read around 60 tags per second [1] within a read range of several meters [2]. Considering a parcel service application for example, it is easy to see that one can have several parcels within few meters. In this case it becomes crucial to know which one is first, on a conveyor belt, and should go to destination X, and which is second and should go to destination Y.

This paper assesses the possibilities for localization using the features of the RFID technology native to passive UHF tags. A simple, one dimensional case is considered with the goal of identifying the order of tags along a line.

II. BACKGROUND

Unfortunately a single, universal scheme for localization is hard to derive, as RFID is a very diverse technology. Therefore, a number of assumptions and generalizations regarding the radio interface and the actual implementation are imposed here.

2.1 Physical layout

In the paper, a typical industrial application is considered, consisting of a conveyor belt and a gate. The conveyor belt moves object, with tags attached, through the gate, which is the reading point. The objects (therefore the tags as well) are assumed static with respect to the belt. This is an important assumption but can be justified, since many industrial systems have trays on the belt, constraining any movement. A typical value for the belt speed is about $2\ m/s$.

2.2 Communication format

Only passive tags are considered, working in the UHF frequency band, which is around $868\ MHz$ for Europe [3]. The passive tags suggest somewhat limited amount of data. A typical value is $2\ kbits$ as stated in [2]. Since the whole system is in the microwave range, modulated backscattering is used for transmission. Once powered, the tag starts to switch its chip input impedance, corresponding to the data stored. This results in matching or mismatching the tag's antenna ports and therefore, the reflected (backscattered) power, which effectively leads to ASK modulation of the returned signal.

With these main parameters specified, the communication timing format can be shown (Fig. 1). As it can be seen, most of the time is the actual data transmission and only a very short period is used for control commands. This period slightly increases if more tags are active and anti-collision protocols are deployed. With the specified frequency, the wavelength is $34.6\ cm$, which, combined with the belt speed, yields some $11\ cm$ for the whole communication in the space domain. The whole process from activation, to idle state, ready for reactivation, takes approximately $55\ ms$.

III. SIMULATIONS

Typically the antennas of a commercial system are placed at the four sides of the gate (top, left, right and bottom for example) with the sole purpose of acquiring a valid read response. They are usually directive, patch antennas, switched in a certain order, one after another.

Here, a similar approach is used, but dipoles are selected to create an array with a null in the reader field. A dipole is simple to describe mathematically in its far field region, and has a well defined null in the radiation pattern along the z axis [4]. The field components are as follows:

$$E_r \approx E_\phi \approx 0$$

$$E_\Theta \approx j\eta \frac{kI_0}{2\pi r} e^{-jkr} \left(\frac{cos\left(\frac{kl}{2} cos\Theta\right) - cos\left(\frac{kl}{2}\right)}{sin\Theta} \right)$$

where j is the imaginary unit, $k = \frac{2\pi}{\lambda}$ is the wavenumber, I_0 is the current on the dipole, l is the length of the dipole, r is the distance from it and Θ is the elevation angle.

In the simulation, the dipoles are also placed on the four sides of the gate, where each dipole is tilted to steer the null at the belt in front of the gate. This narrows the activation field and helps isolate tags. The main optimization parameter is the tilt angle. The simulations are conducted without any noise, reflections or polarization losses (a major issue later) into account. Only oversimplified, idealistic evaluation is desired since measurement data is provided later. The output from the code has been verified against reference material such as [4].

The result can be seen on Fig. 2 (two way (round trip) communication shown). The four dipoles are presented with different lines (the responses of the two sides are identical therefore only three lines are visible). A somewhat flat region is formed in the beginning of the graph, with insufficient power for activation. Then the field experiences a null and in front of the gate the field strength grows and becomes large enough to awake the moving tags.

Taking the phase gradient of the received signal, the mean dopler shift can be extracted. The zero crossing of the gradient corresponds to zero doppler shift. This occurs when the tag is under the antennas and is used as an indicator of the moment of passing through the gate ($< \frac{d\phi}{dx} > \propto < f_d >$, [5], where ϕ is the signal phase, dx is the elementary spatial displacement and f_d is the doppler frequency). Of course, in this idealistic case even the peak power can be used but when all the noise, fading, shadowing etc. of a real system are taken into account, this becomes difficult.

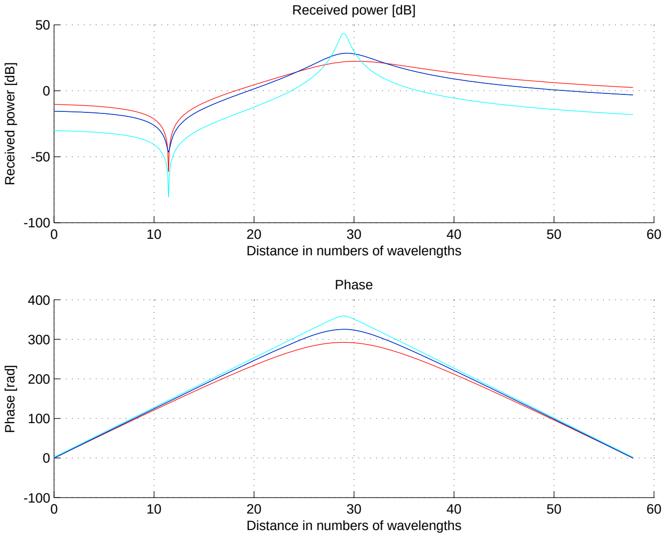

FIGURE 2 - SIMULATED RECEIVED SIGNAL AT THE FOUR DIPOLES (ROUNDTRIP)

Notice, that although the tags are considered to be in the far field of each individual antenna, they are not in the far field with respect to the whole array. This is also true for the measurement set-up shown next.

IV. MEASUREMENTS

The goals of the measurements are to:

- confirm / reject the proposed antenna array as activation selective by comparing it to a standard array
- acquire data of the tag's response in a real world environment with all propagation effects: noise addition, shadowing, multipath, etc.
- determine, based on the data, a simple common signal processing algorithm that accounts for different variations of tag placement, polarization etc.

To achieve these goals two types of experiments are conducted. First activation selectivity is tested with live GEN2 tags and a commercially available reader and then sounding equipment is used to record the responses from two different arrays.

4.1 The set-up

The experimental set-up consists of a wooden rectangular cage, and a cart with wheels, that represents the moving conveyor belt. Two sets of antennas are placed on the cage forming two gates (again, these are the reading points).

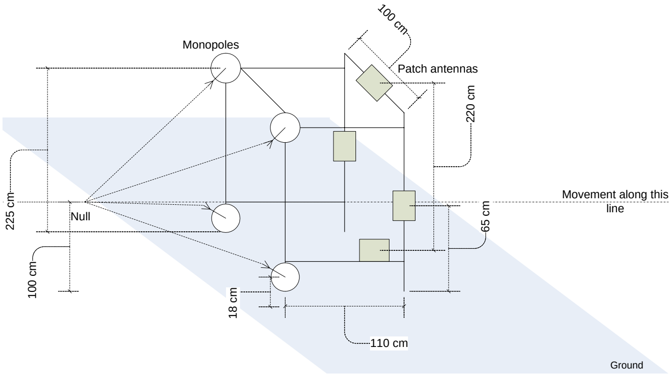

FIGURE 3 - EXPERIMENTAL SET-UP - CAGE DIMENSIONS

The first set comprises of four monopoles. They form an array with similar properties to the one simulated. Monopoles are suitable for the task, since they have almost the same radiation pattern as dipoles - covering half plane only. The second array is built from commercially available patch antennas from Kathrein Inc. [6]. The dimensions of the cage are shown in Fig. 3.

4.2 The tags

For the activation test live GEN2 tags [3] are used while for the sounding, a tag antenna, with the chip removed, was used. In the latter case the antenna is fed optically to avoid undesired cabling effects [7]. The actual device can be seen on Fig. 4.

4.3 The sounder

A direct correation sounder [8] is used, transmitting single channel pseudo noise (PN) sequence (feeding the tag). Eight receive channels record the responces from the eight antennas. The transmit frequency is 870 MHz and the power transmitted is -9 dBm. The distance over which the measurements are taken is 9 m and the cart travels this distance, pulled by a step motor, within 194 $secs$. A tachometer was used to synchronize the cart movement with the sounder timing.

To meet the Nyquist criterion the sampling frequency is chosen to be 1.7 Hz, which gives some 330 samples per antenna for the whole 9 meters i.e. 2.72 cm for each sample or about 13 samples per wavelength.

Since the data rate is much higher (40 $kbit/sec$) than the sampling rate, averaging over several symbols provides accurate signal detection. Subject to future work is to determine what is optimal: averaging of all symbols, averaging of only ones or only zeros. For the purposes of this paper it is assumed that whatever averaging is used, it does not introduce any sudden phase shifts due to the matching and mismatching of the antenna input impedance. This is a fair assumption, since the phase shift (if any) will be the same for all equal symbols and can be filtered.

The sounding measurements are done by recording the impulse responses at the eight antennas with a bandwidth of 20 MHz. Since RFID is a narrow-band technology only the center frequency is used later on. All signal processing is done in the time domain.

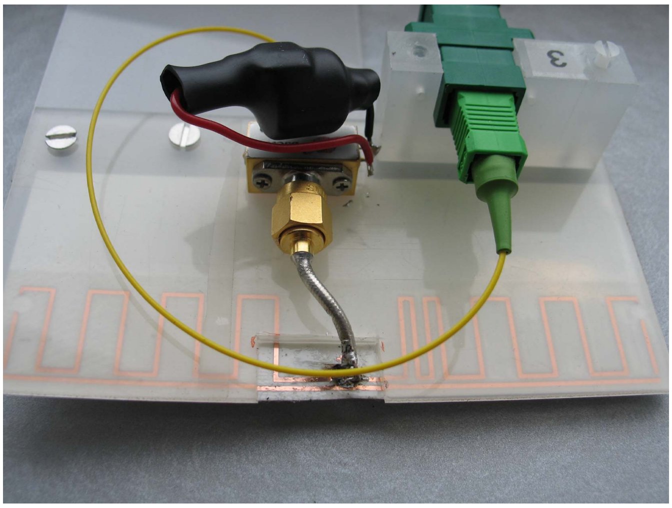

FIGURE 4 - TAG ANTENNA WITH REMOVED CHIP FOR SOUNDING. FEEDING IS DONE OPTICALLY.

4.4 Activation measurements

The activation selectivity of the two arrays is measured with a commercially available reader from Intermec Inc. (Model: IF5 [9]). The reader supports up to four antennas and the two arrays were tested one after another.

Five live GEN2 tags were placed on the cart in different locations and positions, and run through the cage (Fig. 5). The number of reading antennas and read tags was recorded from the first response to where the reading stops. This results in an average number of valid responses as a function of space with respect to the array's position.

Unfortunately only strongly linear polarized tags were available and since the monopoles are also linear polarized, this selectivity test was inconclusive. Even with properly aligned tags in one position, as the cart moves the alignment is lost (moreover the monopoles are omni-directional). The patch antennas on the other hand, are circular polarized (and directive) and have no polarization issues with the linear tags. The power traces from the sounding measurements also reflect this. The monopoles signal is 5 to 10 dB lower on the average.

4.5 Sounding measurements

When doing the sounding measurements the tag (Fig. 4) was placed in various positions on two types of objects - a deterministic one (a box) and a non-deterministic one (a sport bag). These different positions represent different signal patterns.

Considering a parcel service, for example, one can eliminate some ambiguity with respect to the tag's orientation. Obviously, in this case the tag can be either vertical (when on the sides of the box) or horizontal (when placed on top or bottom). It is expected that there will always be one antenna reading strong signal with direct line of sight (except when on the bottom). Also in this case different polarizations can be investigated. Cross-polarization between the tag and the monopoles in this case, leads to weaker and more corrupted signal, but not a total loss of communication, which was the case with the activation test.

The non-deterministic case allows for more degrees of freedom. The tag can be in any position and the radar cross-section and polarization are completely unpredictable.

FIGURE 5 - EXPERIMENTAL SET-UP - CAGE WITH TWO ARRAYS (TWO GATES)

All possible variations of the box sides were measured twice plus five random positions of the bag. Vertical and horizontal orientation was used for the box measurements. The idea behind these variations is to test most typical situations and see if localization is possible for all of them or only few special cases.The time of the passing of the tag, through the two arrays, was measured and from that the actual sample number of the passing is derived.

Actual measured data can be seen in Fig. 6 (tag placed on the right side of the box (top two lines) and a random tag position on the bag (lower two lines), top patch and top left monopole plotted in both cases). The two passing points, through the two arrays are clearly visible.

V. LOCALIZATION

Here, a simple algorithm is proposed that can be used to localize the passing tags. The algorithm was applied to the measured data and an order of wavelength accuracy was achieved.

The algorithm is based on phase detection from which the mean dopler shift is derived. As it was seen in the simulation (Fig. 2), as the tag approaches the gate, the phase grows, reaches a maximum at the passing point, and then drops down. On the measured data this is masked by a lot of noise, introduced by the various propagation effects. It is difficult to tell straightforward where the peak is. Moreover the four different antennas from each array, have different peak positions.

To clean up the noise few simple steps are proposed. First the phase peaks are found from the raw data and outliers are detected. Then the mean powers, around these phase peaks are calculated and the measurements are weighted accordingly. Smoothing filter is ap-

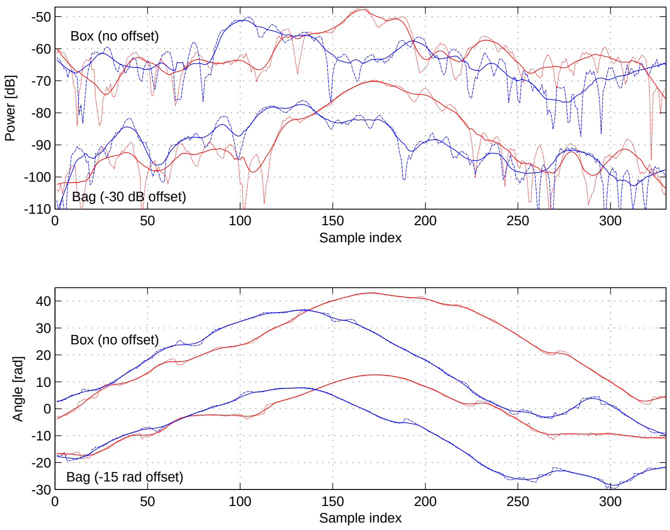

Figure 6 - Measured power and mean phase for one of the monopoles (blue) and one of the patch (red) antennas. Box and bag traces shown. (The thick lines are smoothed versions of the actual data (thin lines))

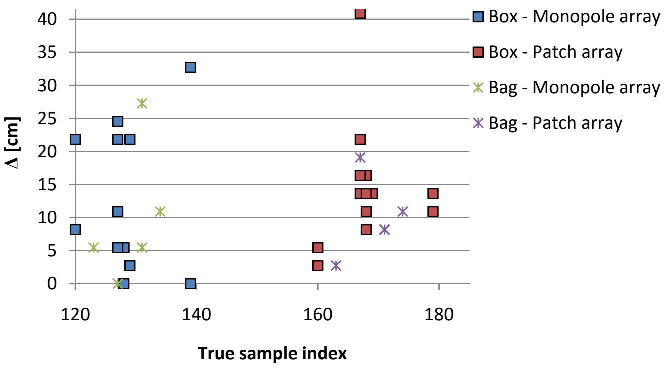

Figure 7 - True sample index of passing and the difference of the estimated index

plied afterwards. Finally the measurements are averaged and the new, estimated peak phase is extracted.

In an actual implementation, the tags would start responding when activated and continuously be polled. This leaves a trace of responses until the tag is outside the reader's field. After that, the reader can process the trace, using the proposed algorithm.

Applying this process to the measured data the following results were received (Fig. 7). The difference of the estimated sample index of passing from the true sample index ($\Delta = estimated\_index - true\_index$) is shown in centimeters to give an idea of the accuracy. Simple statistics are shown in Table 1

Table 1 - Mean Δ and standard deviation

		Monopole array	Patch array
Box	Mean Δ	11.9 cm	14.4 cm
	Standard deviation	10.5 cm	9 cm
Bag	Mean Δ	9.8 cm	9.8 cm
	Standard deviation	10.5 cm	6 cm

The estimation data presented includes all measurements - deterministic case, as well as non-deterministic case. This comes to show that even with an algorithm as simple as the proposed one, localization is possible in various scenarios. As a result the position ambiguity (Δ) is shrunk from several meters (in-field/out-of-field detection), to some tens of centimeters i.e. order of magnitude improvement.

The proposed algorithm utilizes simple smoothing as a filtering function but more advanced filters are also possible. For example, a Kalman filter is a possible solution as it will account for the way the phase changes and include all measurements into the estimation.

Finally, linear regression (or any other fit) can be applied to the phase gradient in an attempt to find a zero crossing that also identifies the passing point. The concrete choice of algorithm will highly depend on the application.

VI. Conclusion

The paper looked at the possibilities for spatial localization of RFID tags within the interrogator field. Because of the wide implementation range of the RFID technology only passive UHF tags were considered. Based on the radio specifications of the latter the local mean dopler shift of the backscattered signal was identified as a location determining quantity.

A simple antenna array was simulated proposing activation selectivity. The array is optimized for performance and the conclusions are experimentally tested with live tags and commercially available reader.

Using sounding equipment, the responses from two antenna arrays are recorded. A variety of situations were tested to ensure independence of the result from factors like line of sight, polarization, multipath etc. Two types of objects, with deterministic shape and with random shape, were used to cover most typical cases and applications.

Finally a simple signal processing algorithm was proposed to be used for localization. Compared to standard implementations, the results show order of wavelength accuracy, which can be used in new applications like fine sorting.

References

[1] Karthik Narayanan Moncombu Ramakrishnan. *Performance Benchmarks for Passive UHF RFID Tags*. PhD thesis, B.E., Electronics and Communication Engineering, College of Engineering, Guindy Anna University, Chennai, India, 2003.

[2] Klaus Finkenzeller. *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*. John Wiley & Sons, Ltd., second edition, 2003.

[3] EPCglobal. *Class 1 Generation 2 UHF Air Interface Protocol Standard Version 1.0.9: "Gen 2"*, January 2005.

[4] Constantine A. Balanis. *Antenna Theory: Analysis and Design*. John Wiley & Sons Inc., second edition edition, 1997.

[5] Patrick Claus F. Eggers and Jørgen Bach Andersen. Measurement of complex envelopes of mobile scenarios at 450 mhz. *Transactions on Vehicular Technology*, 38(2):37–42, May 1989.

[6] Kathrein Inc. Scala Division. http://www.kathrein-scala.com/catalog/25-200.pdf.

[7] Wim Anton Theo Kotterman, Gert Frølund Pedersen, Kim Olesen, and Patrick Claus F. Eggers. Cable-less measument setup for wireless handheld terminals. In *12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, volume 1, pages 112–116, 2001.

[8] J. Ø. Nielsen, J. B. Andersen, P. C. F. Eggers, G. F. Pedersen, and K. Olesen. Measurements of indoor 16x32 wideband mimo channels at 5.8 ghz. *Proceedings of the 2004 International Symposium on Spread Spectrum Techniques and Applications*, pages 864–868, August 2004.

[9] Intermec Inc. http://intermec.com/products/rfid2_if5/index.aspx.