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Potential of RFID Systems to Detect Object Orientation

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***Abstract*—In this paper we present a novel method for estimating the inclination of passive UHF RFID tags, for use in supply chains to monitor the handling of tagged items. Based on observations of the polarization, a Bayesian estimator of the tag inclination is constructed. The Bayesian estimator has been analyzed and evaluated in a experimental setup. The results shows great potential as the estimator is very robust when determining the inclination.**

I. Introduction

The technology of Radio Frequency IDentification (RFID) has been widely deployed in supply chain applications, as it among others enables a high identification rate, a higher level of automation, and control of every aspect of the supply chain. Today various items are therefore transported and handled by automated systems with a minimum of human interaction. Some of these items might be fragile, like chinaware, domestic appliances or electronic equipment, such as LCD televisions. It is desired that items like these are handled carefully. Some of the boxes may even have a *This side up* marker, meaning that the orientation of the box is important and should be sustained.

In this paper we present a method for identifying the orientation of an RFID tagged object. By monitoring the orientation of an object throughout the entire supply chain a logistic service provider can use the data to prove a certain quality of service, or identify in which segments of the supply chain the items received a rough handling.

The main idea is to identify the orientation of an object through the orientation of the tag attached to it. If it is only desired to identify whether an object has fallen over, only a single tag and its inclination is required. However, if the orientation in three dimensions is desired, each object must be fitted with multiple RFID tags marking the dimensions of the object in three-dimensional space. By identifying the inclination of each tag, we can identify the orientation of the object. This is achieved using multiple reader antennas, each measuring the polarization of the signal, received from each tag. From the observations by each reader antenna, a Bayesian estimator of the object orientation is constructed.

Estimating the inclination of a tag based on its polarization is, to the best of our knowledge, a novel idea, albeit polarization have been used for different purposes previously.

In the area of location based services, localization of RFID tags is an emerging research area. Methods for localization based on ranging in an indoor environment are subject to large errors. In [1], [2] methods for estimating the loss due to polarization mismatch is presented, in order to improve the precision of the final estimated location.

Polarization diversity is another way of utilizing polarization, and is investigated in [3]–[5] as an alternative to spatial diversity. Here co-located antennas use orthogonal polarizations to achieve a diversity gain. This is for example used in radar systems to better detect targets of small radar cross section. [6]

In this paper we assess the potential of an RFID system to detect the orientation of a tagged object. In our experiments we use co-located antennas for the RFID reader, to decompose the received signal into two orthogonal signal components, in order to determine the polarization of the received signal. With multiple reader antennas sampling the polarization of the tag reply, their observations can be combined in a Bayesian estimator of the physical orientation of the tag antenna.

The remainder of this paper is organized as follows: In section II the system environment is described along with the assumptions made in this work. Section III describes the analysis of the polarization and construction of the Bayesian estimator. This estimator is evaluated in an experimental setup, and the results are presented in section IV. The final concluding remarks are given in section V along with options for future work.

II. System Model

The proposed system is targeting supply chain applications, and is presumed to be installed in an indoor environment, for example as a part of a production line in a factory, or inside the cargo hold of a lorry. The latter represents a more confined and reflective environment, than the former. In such scenarios items are often packed in boxes or crates, and placing an RFID tag on the sides of these boxes effectively reduces the possible inclinations of the tag to either vertical or horizontal.

To meet the supply chain application, we start in this work by investigating a simple case. We use passive UHF tags, as the lack of battery results in a cost effective and environmental friendly product. The tags are assumed to follow the EPC Global Gen 2 standard [7]. When each item is fitted with three tags, one for each spatial dimension, the anti collision algorithm in the Gen 2 standard ensures that each individual tag has a chance to transmit. This means that we can proceed considering a scenario with a single tag, which simplifies the experimental evaluation.

To increase the statistical certainty of the estimated inclination we assume that the RFID reader covers the interrogation zone using multiple antennas, in order to have multiple independent samples of the Received Signal Strength (RSS). Moreover, each antenna collects multiple samples over time of the received signal. The utilized antennas are dual linearly polarized, enabling decomposition of the received signal into two orthogonal components, namely a vertical and a horizontal electromagnetic field component, E_θ and E_φ, respectively. The received signal, y, can therefore be written as a tuple of signals, y_θ and y_φ:

$$y_\theta(m,n) = h_\theta(m,n)x + z_\theta$$
$$y_\varphi(m,n) = h_\varphi(m,n)x + z_\varphi$$

Where the indexes m and n refers to the reader antenna id, and the sample number, respectively. The transmitted signal is denoted x, and z refers to the thermal noise in the reader antenna. The channel coefficient h represent the fading in an indoor environment, where reflecting objects distort the wireless transmission. Since tags can be placed on any side of an object, Line Of Sight (LOS) may not be available. Hence, the power of the received signal, denoted Y, is assumed to follow an exponential probability distribution, characterized by a single parameter, the mean power σ. The inclination of the tag introduces a polarization mismatch between tag and reader antennas, this affects the mean power making σ dependent of β.

With the reader antennas distributed around the interrogation zone, their received signal will be affected by different parts of the environment, so the channels experienced by each antenna, i.e. $h(m,n)$ for $m = 1,\ldots,M$, will be independent. Moreover, when each antenna collects multiple samples of the RSS, i.e. $n = 1,\ldots,N$, each sample experience approximately the same multi-path fading, as the environment seen from each antenna is constant. However, it is assumed that these samples are conditionally independent if the orientation is known, in order to simplify the construction of the Bayesian estimator.

With the signal model and the corresponding assumptions described, the proposed method for estimating the object orientation can be analyzed in details.

III. Analysis

The Bayesian estimator of the tag inclination is based on two key aspects; 1) The inclination of the linearly polarized signal received from the tag, and 2) The assumption that the two orthogonal components of the received signal are uncorrelated throughout the wireless channel. These aspects are therefore described before presenting the Bayesian estimator.

A. Polarization Primer

The polarization is defined as the orientation of the electric field with respect to the direction of propagation. Most UHF tags antennas are variants of a dipole [8], and have a linear polarization. This means that the polarization vector, defining the magnitude of the electrical field, is a tangent to the half-circle connecting the two ends of the antenna. Hence, the polarization vector and the conductor of the dipole are not necessarily parallel, but they will always lie in the same plane, as illustrated in Fig. 1.

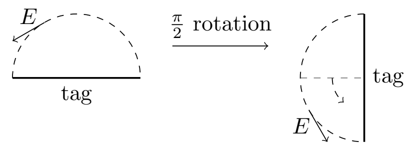


Fig. 1. Polarization of a dipole antenna.

When a tag is rotated, its linear polarization is rotated as well. It is desired to estimate the inclination, i.e. the angle, β, of this polarization with respect to a vertical orientation.

To measure the polarization we use two orthogonal measurements of the RSS, provided by dual-polarized reader antennas. The magnitude of the vertical and horizontal field components is given by the field vectors $\overline{E_\theta}$ and $\overline{E_\varphi}$, respectively. The angle β seen from a receiving antenna is then given by:

$$\beta = \arctan \frac{|\overline{E_\varphi}|}{|\overline{E_\theta}|} \tag{1}$$

By combining observations of β from several antennas, a reader can increase the statistical certainty about the estimated inclination, $\hat{\beta}$.

B. Correlation of $y_\theta(m,n)$ and $y_\varphi(m,n)$

When an electromagnetic wave hits an object, e.g. a wall or the ground, its energy is partly absorbed, with the absorption coefficient depending on the material of the object. The remaining energy is reflected as a attenuated replica of the original signal.

As an example consider a tag transmitting a signal x_t. The tag is approximately oriented horizontally, so x_t can be decomposed into two orthogonal components, $\overline{E_\theta}$ and $\overline{E_\varphi}$, where $|\overline{E_\theta}| \ll |\overline{E_\varphi}|$:

$$x_t = \overline{E_\theta} + \overline{E_\varphi} \tag{2}$$

Both $\overline{E_\theta}$ and $\overline{E_\varphi}$ are field vectors of the electrical field and perpendicular to the direction of propagation.

When a smooth surface reflects a signal, the signal component parallel to the reflecting surface is reversed, i.e. the orthogonal components do not mix. Unfortunately most indoor surfaces are rough, and then the signal components mix upon reflection. This means that even though x_t is transmitted in one dimension it will, after sufficiently many reflections have equal power on the two orthogonal polarizations.

With multiple reader antennas covering the same interrogation zone, it is reasonable to assume that at least one antenna has LOS to the tagged object. The approach presented in this paper is based on the observation that the LOS component is dominant compared to the reflections from the environment. Hence we assume that the orthogonal components of the received signal, $y_\theta(m,n)$ and $y_\varphi(m,n)$, have low correlation and fade individually, due to the environment. This is an approximation that helps simplify the construction of the Bayesian estimator, but it may be degraded in setups where LOS is absent.

C. Bayesian Estimator

The estimated inclination, $\hat{\beta}$ is constructed as a Bayesian estimator, based on observations of the signal strength. As mentioned in Section II, each receiving antenna measures the RSS in both the horizontal and vertical polarization creating the tuple $Y_\theta(m,n)$ and $Y_\varphi(m,n)$. To simplify notation we write the observations from the M reader antennas as a vector, so $\overline{Y_\varphi}(n) = [Y_\varphi(1,n),\ldots,Y_\varphi(M,n)]$ and represents the dataset containing the $n-$th RSS sample in horizontal polarization for all M reader antennas. The a posteriori probability of β, given the observed RSS, is then given by:

$$P(\beta|\overline{Y_\theta}(n),\overline{Y_\varphi}(n)) = \frac{P(\overline{Y_\theta}(n),\overline{Y_\varphi}(n)|\beta)\cdot P(\beta)}{P(\overline{Y_\theta}(n),\overline{Y_\varphi}(n))} \quad (3)$$

We are interested in the Maximum A posteriori Probability (MAP) of the orientation angle β given the observed dataset. Since the denominator of Eq. (3) is independent of β we focus on the numerator when estimating the inclination:

$$\begin{aligned}P(\beta|\overline{Y_\theta}(n),\overline{Y_\varphi}(n)) &\propto P(\overline{Y_\theta}(n),\overline{Y_\varphi}(n)|\beta)\cdot P(\beta)\\ &= P(\overline{Y_\theta}(n)|\beta)\cdot P(\overline{Y_\varphi}(n)|\beta)\cdot P(\beta) \quad (4)\end{aligned}$$

Where the likelihood, $P(Y(n)|\beta)$, refers to the exponentially distributed RSS, where β affects the mean received power as described in Section II. The a priori knowledge of β is given by the prior distribution $P(\beta)$. Initially nothing is known, hence β is assumed to be uniformly distributed. Since the RSSs received by M reader antennas are independent the resulting a posteriori probability is given by:

$$\begin{aligned}&P(\beta|\overline{Y_\theta}(n),\overline{Y_\varphi}(n)) \propto\\ &\quad\left\{\prod_{m=1}^{M} P(Y_\theta(m,n)|\beta)\cdot P(Y_\varphi(m,n)|\beta)\right\}\cdot P(\beta) \quad (5)\end{aligned}$$

If we let each reader antenna collect multiple samples of the RSS we can update the prior based on the previous observations. As an example consider the a posterior distribution based on two successive observations, i.e. $N = 2$:

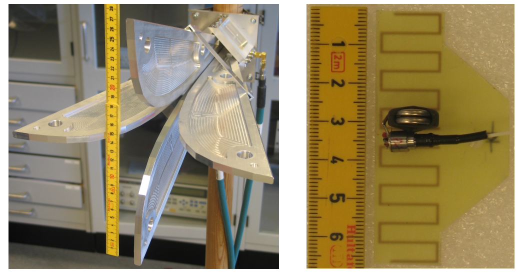
$$\begin{aligned}&P(\beta|\overline{Y_\theta}(1),\overline{Y_\varphi}(1),\overline{Y_\theta}(2),\overline{Y_\varphi}(2)) \propto\\ &\quad P(\overline{Y_\theta}(2),\overline{Y_\varphi}(2)|\beta)\cdot \underbrace{P(\overline{Y_\theta}(1),\overline{Y_\varphi}(1)|\beta)\cdot P(\beta)}_{\propto P(\beta|\overline{Y_\theta}(1),\overline{Y_\varphi}(1))} \quad (6)\end{aligned}$$

From Eq. (6) we see that for each succeeding observation we can use the posterior distribution, calculated from the preceding observation, as an updated prior distribution. This makes the complexity of calculating the Bayesian estimator, $\hat{\beta}$, increase linearly with the number of observations. Letting each antenna collect N observations gives the following recursive posterior probability:

$$\begin{aligned}&P(\beta|\overline{Y_\theta}(N),\overline{Y_\varphi}(N)) \propto\\ &\quad P(\overline{Y_\theta}(N),\overline{Y_\varphi}(N)|\beta)\cdot P(\beta|\overline{Y_\theta}(N-1),\overline{Y_\varphi}(N-1)) \quad (7)\end{aligned}$$

The estimated inclination is then given by the MAP:

$$\hat{\beta} = \operatorname{argmax}_\beta \left\{P(\beta|\overline{Y_\theta}(N),\overline{Y_\varphi}(N))\right\} \quad (8)$$



(a) Reader antenna (b) Tag

Fig. 2. Antennas used as reader and tag antennas, respectively, in the experimental setup.

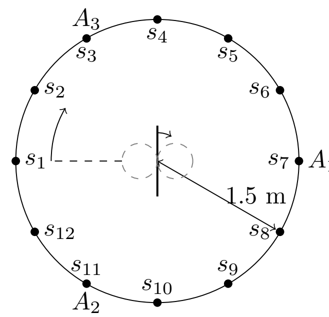


Fig. 3. The experimental setup, with the three reader antennas placed on a circumference around the tag, in a distance of 1.5 m. The tag antenna is then rotated in azimuth, in 12 steps of $\frac{\pi}{6}$ radians.

IV. Results

The Bayesian estimator, $\hat{\beta}$ from Eq. (8), is evaluated in an experimental setup in an indoor office environment. We utilize three dual-polarized horn antennas as RFID reader antennas, i.e. $M = 3$. One is depicted in Fig. 2(a), along with the utilized tag antenna in Fig. 2(b). We use a folded meander dipole antenna printed on PCB, as tag antenna, and to power the antenna we fitted and optical diode on the antenna and used optical cables for the signaling. This removed the electromagnetic influence of copper cables, making the meander antenna operate approximately like a real RFID tag.

The horn antennas, denoted A_1, A_2 and A_3, are placed at a distance of 1.5 m from the tag, and evenly spaced in a circle around it, as illustrated in Fig. 3. This is a constraint of the utilized setup, but as we are only pursuing the assessment of the potential of estimating the orientation, this setup is used as a starting point. Experiments with the tag placed randomly between the reader antennas, and thereby favoring one antenna over the others, are planned for future work.

The tag and reader antennas are raised 1 m and 1.85 m above ground, respectively, creating a difference in hight of $0.85\ m$. This can be seen from the environment, which is a lab and office environment, depicted in Fig. 4. This represents a normal indoor environment with lots of reflecting objects and surfaces.

In the targeted supply chain application the tag is assumed to be placed on the side of some box, e.g. vertical oriented, and if the box is knocked over the tag is then oriented horizontally, or vice versa. This means that the inclinations of interest are

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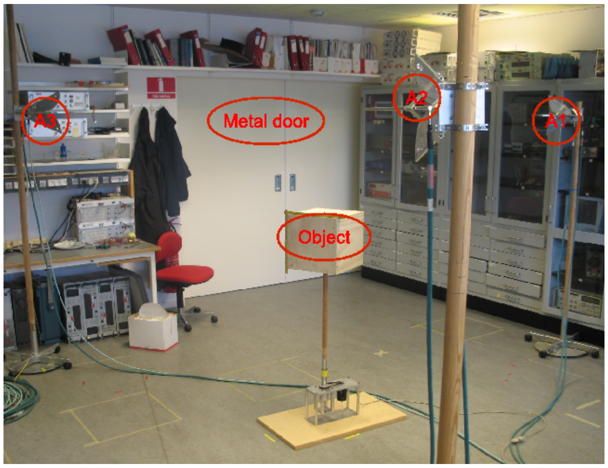
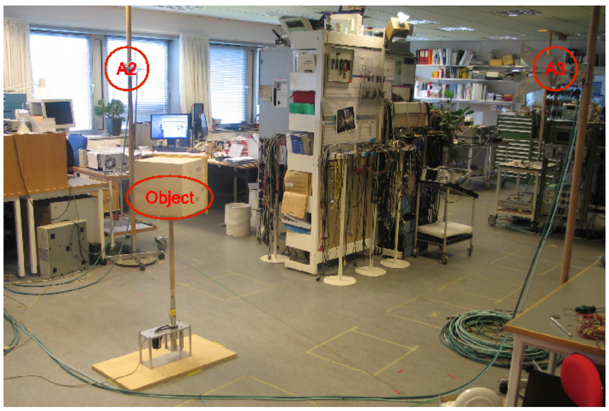


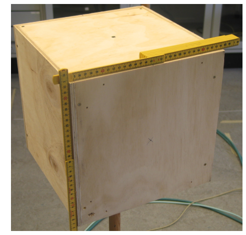
(a) From eastern corner.



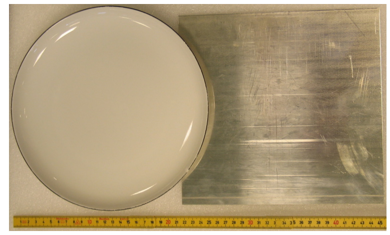
(b) From western corner.

Fig. 4. The experiments are conducted in a lab and open office environment.

(a) Cardboard box.



(b) Plywood box.



(c) Metal and porcelain plates.

Fig. 5. Objects used in the experimental setup.

Parameter:	Setting:
#reader antennas (M)	3
#observations (N)	4
Inclination angles (β)	$\{0, \frac{\pi}{4}, \frac{\pi}{2}\}$
Azimuth angles	$\{\frac{\pi}{6}, \frac{2\pi}{6}, \ldots, 2\pi\}$
Objects	1) Cardboard box with a porcelain plate 2) Cardboard box with a metal plate 3) Plywood box

TABLE I
PARAMETERS FOR THE EXPERIMENTAL SETUP.

vertical and horizontal, $\beta = 0$ and $\beta = \frac{\pi}{2}$ respectively, and additionally we use a tilted inclination, $\beta = \frac{\pi}{4}$, i.e. in total three different inclinations are measured.

Since the tagged objects can be oriented in any direction we need to test in the entire azimuth spectrum. Hence, for each inclination the tag is rotated 2π radians in 12 steps of $\frac{\pi}{6}$ radians, denoted s_i, where $i = 1, \ldots, 12$, as illustrated in Fig. 3. In each step each reader antenna measures the two dimensional RSS from the tag. This is repeated four times giving each antenna four independent observations of the RSS in each azimuth orientation, i.e. $N = 4$. The exponential distribution describing the likelihood is characterized by a single parameter, the mean power of the RSS, σ. Using the dataset of measured RSSs, σ is calculated for each inclination respectively, as the mean RSS across all azimuth orientation and all repetitions.

This procedure is repeated for four different scenarios; One with the tag antenna by itself, and three where the tag is attached to different objects. It is expected that the objects will affect the radiation of the tag antenna, hence the size and material of the objects must represent real life object that can occur in a supply chain. We have used a porcelain plate, and a metal plate, both protected by polystyrene and packed in a cardboard box ($21 \times 24 \times 30$ cm), and as the third object an empty box of plywood ($30 \times 30 \times 30$ cm) was utilized.

The parameters for the experimental setup are summarized in Table I.

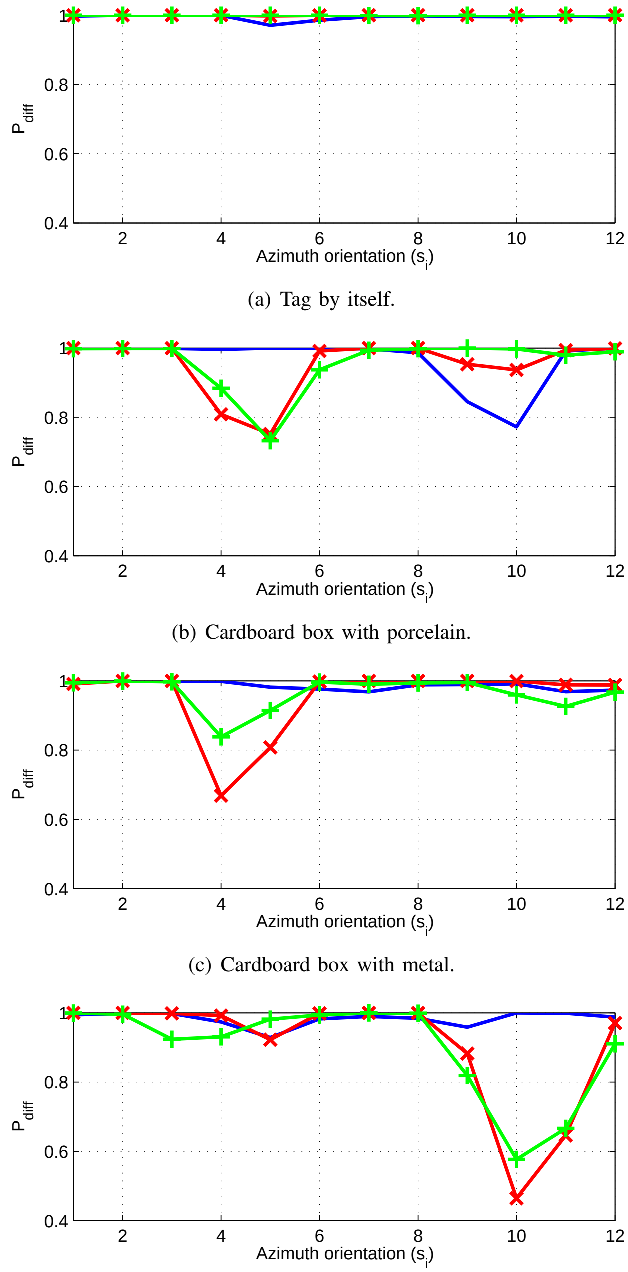
In Fig. 6 the results from each of these four scenarios are plotted. To easier obtain an overview of the results we have defined a new metric, the a posteriori difference, denoted P_{diff}. This is defined as the difference between the posterior probability for the *true* inclination, β_{true}, and the maximum posterior of the two remaining inclinations, β_{r1} and β_{r2}:

$$P_{diff} = P(\beta_{true}|\overline{Y_\theta}(4), \overline{Y_\varphi}(4)) - \max\left\{P(\beta_{r1}|\overline{Y_\theta}(4), \overline{Y_\varphi}(4)); P(\beta_{r2}|\overline{\theta}(4), \overline{Y_\varphi}(4))\right\} \tag{9}$$

If P_{diff} is positive it means that the true inclination yields the maximum a posterior probability, and therefore gives the correct $\hat{\beta}$. The closer P_{diff} is to 1 the more certain we are on this decision.

Without any objects disturbing the operation of the tag antenna, the method is very robust, and determines the correct inclination with a large margin for every azimuth orientation, see Fig. 6(a).

The effect from the introduced objects is evident as it decreases the certainty of the decisions. For a cardboard box containing porcelain, in Fig. 6(b), we see a dip to around 0.75 in s_5 for the tilted and vertical inclination, where the horizontal inclination has a dip to 0.8 in s_{10}. When the cardboard box contains a metal plate we see a dip in s_4, in Fig. 6(c), for



(a) Tag by itself.

(b) Cardboard box with porcelain.

(c) Cardboard box with metal.

(d) Plywood box.

Fig. 6. Plot of the difference, P_{diff}, between the posterior probability of the correct inclination and the second largest posterior probability in each of the 12 azimuth steps. The vertical inclination is marked with $+$'s, tilted with $\times$'s and horizontal inclination has no markers.

tilted and vertical inclination, but this time to around 0.65 and 0.85 respectively. These dips are caused by an unfortunate combination of the change in radiation, due to the object material, and the reflectors in the environment, e.g. furniture and cabinets. If the environment were furnished differently we would most likely see a similar effect but at different azimuth orientations.

When the object is a box of plywood we see the most significant effect on the posterior probability, as can be seen in Fig. 6(d). For horizontal inclination, P_{diff} is close to 1 in all azimuth orientations. But for the tilted and vertical inclinations we see a significant dip however, as P_{diff}, in s_{10}, respectively drops to around 0.45 and 0.55. Except for these two cases, the posterior probability for the true inclinations surpass the others with more than 0.6, for any abject and orientation. This is considered sufficient for making a confident decision.

It should be noted that the azimuth orientations resulting in severe dips in posterior probability should be avoided if the system is used in a supply chain application. In the utilized indoor environment examples of good azimuth orientations are s_1, s_2, s_7 and s_{12}. As mentioned above this depends on the reflecting surfaces in the environment, and for another environment the good azimuth orientations will be different.

V. Conclusion

In this paper we have presented a novel method for identifying the inclination of a UHF RFID tag. The method is targeted at supply chain applications as a way to monitor the handling of fragile items tagged with passive RFID tags. By monitoring the inclination of these tags, it can be identified when items have been knocked over or been subject to a rough handling. The tag inclination is estimated by a Bayesian estimator based on observations of the polarization of the signal received from the tag at multiple reader antennas.

The method have been analyzed, and evaluated in an experimental setup with the tested tag antenna attached to different objects. The results shows great potential, as the Bayesian estimator proves very robust, and gives the correct tag inclination for all possible azimuth orientations.

For future work it would be interesting to evaluate the proposed method when the tagged object is placed at random between the reader antennas, i.e. favoring one of the antennas, and also include multiple tags on each object.

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