RSSI-Based Maximum Likelihood Localization of Passive RFID Tags Using a Mobile Cart

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***Abstract*—In this paper a maximum likelihood estimator of the locations of passive RFID tags is presented, exploiting the Received Signal Strength Information (RSSI) collected at the reader. The reader-antenna is fixed on a moving cart and collects RFID data in the area of interest. Locations of the reader-antenna and of the target-objects are obtained by the RSSI of "reference" tags placed at known positions. The proposed method can be applied using commercial RFID equipment. Measurements were conducted in an office environment; mean error of 25cm with standard deviation equal to 12,4cm is recorded. Localization accuracy can be further improved by increasing the density of the "reference" tags and the number of reader antennas.**

Localization, RSSI, RFID, Maximum Likelihood Estimation.

I. Introduction

Radio Frequency Identification (RFID) is considered an important building block to bring the "Internet of Things" to life. RFID tags represent a powerful asset to interact with the physical world. Localization capability, i.e. the potential of tracking the position of an object, is considered a fundamental property to provide data with augmented value. In this paper, we present a localization algorithm for tracking battery-less (passive) RFID tags, based only on the measured backscattered power, commonly known as "Received Signal Strength Indication" (RSSI), which is available at any commercial reader.

The localization problem has been treated extensively in prior-art. A summary of related algorithms can be found in [1]. Localization algorithms can be divided in three main categories, based on the physical quantity that is measured: *i*) Direction Finding of the propagating signal [3], *ii*) Propagation-time of the signal [4] and *iii*) Measured Power of the signal (RSSI), [2], [5]. In all cases, localization-accuracy degrades because of multipath.

The proposed method assumes that the reader-antenna(s) is fixed on a mobile cart, which moves around the area of interest, as shown in Fig. 1. Reference RFID tags are placed at known specific locations, while additional RFID tags are attached to the objects that are being traced. The reader antenna identifies all RFID tags within range as it moves across the area of interest, storing their id and their corresponding RSSI value. In order to estimate the position of the reader antenna the maximum likelihood estimator is being used, by taking into consideration only the RSSI of the "referenced" tags. Then, the positions of "target" tags are found by using their corresponding RSSI as described in the next section.

Fig. 1. Representation of a typical scenario.

II. Maximum Likelihood Localization

A. Description of the problem

Consider an area, where passive RFID tags are placed at specific *known* positions, used as "reference" tags. In the same area, passive RFID tags are attached to objects, e.g. products, placed at *unknown* locations. These will be referred as "target" tags. Our purpose is to estimate the locations of the "target" tags. To accomplish that, one (or multiple) reader-antenna(s) is fixed on a moving cart. At each position of the cart, the reader-antenna identifies all passive RFID tags within range (including "reference" and "target" tags), and stores their ID and RSSI value. The method for locating the tags includes two steps. During the first step, the positions of the reader-antenna are estimated by using only the RSSI information from the "reference" tags. Then, during the second step, the positions of the "target" tags are estimated by using the RSSI measurements of the latter, combined with the estimated positions of the reader-antenna derived from the previous step. The method is analytically described below.

B. Estimation of the position of the reader

Assume that the reader is at an unknown position and identifies N "reference" tags with RSSI values P_i, $i = 1, \ldots, N$; let $P = (P_1, P_2, ..., P_N)$ the set of N observations. Denote as r the position of the reader. The conditional probability of r, given the observation set P is defined as:

$$p(r|P) = \frac{p(P|r)p(r)}{p(P)} \tag{1}$$

Note that $p(r)$ is a uniform distribution, and for a given set of observed data, $p(P)$ remains the same over all possible hypothetical values of r, then

$$max(p(r|P)) \equiv \max p(P|r) \tag{2}$$

in other words we can solve the inverse problem. $p(P|r)$ is the likelihood the conditional probability of obtaining a set P of RSSI, from the "reference" tags, given that the true position of the reader-antenna is r. The responses of each "reference" tag are independent, thus

$$p(P|r) = p(P_1, P_2, ..., P_N|r) = p(P_1|r)p(P_2|r)...p(P_N|r)$$

$$p(P|r) = \prod_{i=1}^{N} p(P_i|r) \tag{3}$$

Given observations P and the likelihood function $p(P|r)$, the maximum likelihood estimation of the position r of the reader-antenna is the value of r that maximizes the likelihood function

$$r^* = \underset{r}{\operatorname{argmax}}\, p(P|r) = \underset{r}{\operatorname{argmax}} \prod_{i=1}^{N} p(P_i|r). \tag{4}$$

We had shown theoretically and experimentally in [6]-[8] that the received power level from passive RFID tags is well described by a Rician probability density function. The mean of the Rician pdf is set by the strong Line Of Sight (LOS) component. The standard deviation of the pdf depends on the location of the reader within the room with respect to the location of the tag, as shown in [6] and is not constant in the propagation area. The power of the LOS component at the reader-antenna from the "reference" tag i is:

$$\mu_i^2 = P_{tagi}\tau(P_{tagi})G_{tagi}(\phi_i, \theta_i)G_{ant}(\phi_i, \theta_i)pol(\frac{\lambda}{4\pi d_i})^2, \text{where} \tag{5}$$

$$P_{tagi} = P_{ant}G_{ant}(\phi_i, \theta_i)G_{tagi}(\phi_i, \theta_i)pol(\frac{\lambda}{4\pi d_i})^2. \tag{6}$$

P_{ant} is the reader transmitted power, P_{tagi} is the power at tag i, pol expresses the polarization losses due to the orientation of the tag-antenna with respect to the reader-antenna, G_{tagi}, G_{ant} are tag i and reader antenna gains at the direction of the link defined by the angles ϕ_i, θ_i, and d_i is the distance between tag i and the reader-antenna. Finally, $\tau(P_{tag})$ is smaller than 1 and represents the percentage of the incident power that is backscattered to the reader. The term sizes the non-linearities of the tag-chip; hence it is not constant and depends on the incident power. Furthermore, the part of the incident power that is used for rectification is also included in the term $\tau(P_{tagi})$. This term should be measured for each tag. Equations (5)-(6) assume a monostatic reader antenna configuration. In the case of a bistatic configuration, the direction-vector, the polarization misalignment and the distance should be changed accordingly in one of the two equations.

According to the Rician pdf, the probability density function of the received RSSI P_i given a reader antenna position r is:

$$p(P_i|r) = \frac{\sqrt{P_i}}{\sigma_i^2} e^{-\frac{P_i+\mu_i^2}{2\sigma_i^2}} I_0(\frac{\sqrt{P_i}\mu_i}{\sigma_i^2}) \tag{7}$$

By substituting (7) in (4), the position of the reader-antenna is estimated.

C. Estimation of the positions of the tags

In order to estimate the positions of the "target" tags, the maximum likelihood method is once again used. Assume a "target" tag u at an unknown position r , that has been identified by a reader antenna at K different locations, estimated during the previous step. The set of corresponding RSSI values of tag u, as the reader antenna moves across the area, is denoted as $P_u = (P_u^1, P_u^2, \ldots, P_u^K)$.

By combining equations (4) and (7), as previously, we have:

$$r_u^* = \underset{r}{\operatorname{argmax}}\, p(P_u|r) = \underset{r}{\operatorname{argmax}} \prod_{i=1}^{K} p(P_u^i|r) \tag{8}$$

r_u^* is the position of the "target" tag u that maximizes the above likelihood function.

III. Measurements

The measurements were conducted inside a 4.1m×6.5m office, as demonstrated in Fig. 2. 15 passive UHF RFID tags, namely "ALN-9662 Short Inlay", manufactured by Alien, were arranged at specific location, represented by crosses ("$+$") in Fig. 3. The 5 red crosses represent the "reference" tags that are placed at known positions. The 10 remaining blue crosses represent the positions of the "target" tags that we are trying to locate. The RSSI of all 15 tags was initially measured at the same position and showed a variability within 5dBs. This is a desirable property to evaluate the performance of the method as it approximates well the expected variability of the tags-performance; i.e. when attached to different objects. Furthermore, $\tau(P_{tag})$ was measured by fixing a tag at a specific position, opposite the reader antenna and then reducing the transmission power of the reader P_{ant} 20dBs with a 1dB step, while recording the backscattered RSSI value.

A single reader antenna located on a cart is moved at the specific locations, represented by black stars in Fig. 3 ("$\star$"). The antenna is horizontally tilted towards the area of the tags throughout the measurements as shown in Fig. 2 and is located 20cm above the tags' height. A 10dBic circularly polarized antenna, manufactured by "MTI Wireless Edge", model "MT 242017/NRH" is used. The 3dB azimuth and elevation beamwidth is 65° and 48° respectively.

At each location of the reader-antenna all tags in range are interrogated. The position of the reader is considered unknown

Fig. 2. Photo of the office during measurements.

and must be evaluated based on the RSSI measurements from the known "reference" tags (marked with red crosses). In order to evaluate each location of the reader-antenna, we apply (4) and (7). For each position, only the "reference" tags that have been identified participate in the process. For instance, at location R_1 (see Fig. 3), the reader antenna identified only "reference" tags T_1, T_2 and T_4. Therefore, only the corresponding probabilities will be considered in the likelihood function. The entire room was considered as the search space to our problem.

The 12 estimated positions of the reader-antenna are demonstrated in Fig. 3 with orange stars. The mean absolute error is 33,4cm and the standard deviation is 24cm. The estimated trace is shown with orange dashed line. Notice that the error is larger at the initial position R_1, where all "reference" tags are to the right of the reader antenna and at position R_8, where again all tags are to the left of the antenna. These positions represent the extreme (the margins) of our case-problem, since the reader antenna is typically expected to encounter "reference" tags both to the left and to the right of its location. Furthermore, larger error is recorded when the reader moves away from the tags at positions R_{11}, R_{12}, where the reader is approximately 2m-3m from the "reference" tags; again a situation, which can be handled by dense placement of "reference" tags.

The next step of the algorithm is the calculation of the unknown "target" tags' positions. Now the estimated positions of the reader-antenna from the previous step are used. A vector of 12 estimated reader-antenna positions is available. Equation (8) is applied and the results are shown with black dots ("$\bullet$") in Fig.3. The search space was again the entire room. The locations of the unknown tags agree much better with their actual positions, achieving a mean error equal to 25,3cm with a small standard deviation equal to 12,4cm.

The localization error is smaller than the wavelength of operation, i.e. 34,6cm. The mean error was nearly half the

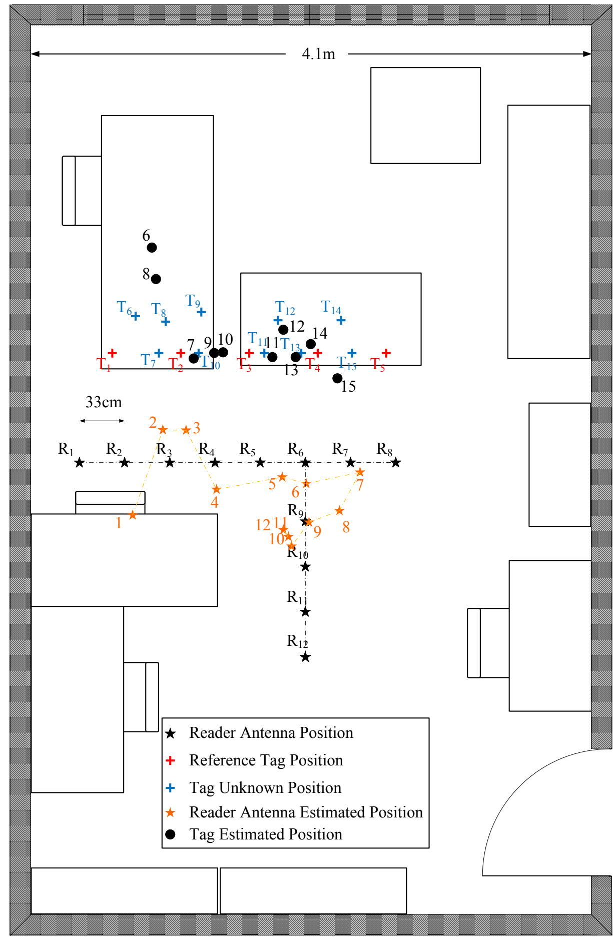

Fig. 3. Representation of the measurements' set-up.

spacing of the reference-tags (50cm) and significantly smaller than the mean error of the reader-antenna trace. This reveals an important advantage of the proposed technique. As the position of the reader-antenna is estimated using the same method, a propagation error that is common in the reference-tag and the "target" tag will be corrected by the algorithm: for instance, if the reference tag and the target tag are both blocked, then the received power will be smaller than expected. As a result, the corresponding reader-antenna position will suffer from a large error. However, the estimated target-tag position (which is the goal of this work) will experience a small error, provided that the target-tag is also blocked similarly to the reference tag. The same principle is expected to correct errors, due to detuning of the tag, when attached to several items, provided that the reference tags experience similar conditions. Hence, the key for the success of the method is to make sure that both reference and target tags are subject to similar link-conditions. This will ensure good accuracy of the method, regardless of the potential errors in the estimated reader-antenna positions. In order to ensure this property, a dense reference-tag grid should be employed.

Another advantage of dense grid-deployment is that much more measurements will be available, thus decreasing fading effects due to averaging. The low-cost of passive RFID tags allow for such dense deployment strategies. A final strategy for the improvement of the accuracy of the method is to deploy multiple transmitting antennas at the cart. Such diversity scheme is expected to increase the number of samples, thus decreasing the error due to fading.

IV. Conclusion

In this work, localization of RFID tags based only on RSSI with commodity hardware has been proposed, by implementing a maximum likelihood estimator. Measurements indicated a mean error of 25cm. The accuracy can be enhanced by increasing the density of ”reference” tags. Further improvement is expected, by increasing the number of reader-antennas. The above techniques are expected to deteriorate the effects of fading.

References

[1] D. Macagnano, G. Destino, G. Abreu, ”A Comprehensive Tutorial on Localization: Algorithms and Performance Analysis Tools,” *International Journal of Wireless Information Networks*, vol. 19, pp. 290-314, Aug. 2012.

[2] E. Alimpertis, N. Fasarakis-Hilliard, and A. Bletsas, ”Community RF Sensing for Source Localization,” *IEEE Wireless Communications Letter*, vol. 3, no 4, pp. 393-396, May 2014.

[3] R. Peng, and M. L. Sichitiu, ”Angle of Arrival Localization for Wireless Sensor Networks,” *2006 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks, 2006*, pp. 374-382, Sept. 2006.

[4] K.W. Cheung, H.C. So,W. -K. Ma, Y. T. Chan, ”Least squares algorithms for time-of-arrival-based mobile location,” *IEEE Transactions on Signal Processing*, vol. 52, no 4, pp. 1121-1130, March 2004.

[5] D. Joho, C. Plagemann, W. Burgard, ”Modeling RFID signal strength and tag detection for localization and mapping,” *IEEE International Conference on Robotics and Automation*, pp. 3160-3165, May 2009.

[6] A. G. Dimitriou, S. Siachalou, A. Bletsas, and J. N. Sahalos, ”A Site-Specific Stochastic Propagation Model for Passive UHF RFID,” *IEEE Antennas Wireless. Propagat. Letters*, vol. 13, pp. 623-626, Dec. 2014.

[7] A. G. Dimitriou, S. Siachalou, A. Bletsas, and J. N. Sahalos, ”Site-specific stochastic propagation model for automated RFID network planning,” *2013 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, pp. 603-606, Torino, Italy, Sept. 2013.

[8] A. G. Dimitriou, A. Boursianis, I. Markakis, S. Siachalou, T. Samaras, and J. N. Sahalos,, ”Comparison of a Fast Probabilistic Propagation Model against an Analytical Computational-EM Model and Measurements for the Evaluation of Passive RFID Systems,” *9th European Conference on Antennas and Propagation*, Lisbon, April 2015.