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Article

Accurate Positioning System Based on Chipless Technology

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Abstract: In this paper, we present an accurate method to localize an object on a 2D plan using the chipless technology. This method requires a single antenna and a chipless tag. Phase difference between a reference position and an unknown position is used to estimate the distances between each resonator and the antenna. Then, multi-lateration is used to determine the position of the chipless tag in the plan. This method provides a better accuracy compared to classical ones based on received signal strength indicator (RSSI) or round-trip time-of-flight. In a square of 10 cm side above the antenna, error over distance determination between each resonators and the antenna is less than 2 mm and localization error on the tag coordinates in the 2D plan is lower than 1 cm. To increase the robustness of this method, we propose also a selection of a subset of the resonators used by the multi-lateration process. This method permits to increase the localization area by more than 20%. All the results have been obtained in real environment, and at different heights to show the robustness of the proposed approach. Finally, localization sensors based on this method can also be used as classical chipless RFID tag for identification with the same coding capacity.

Keywords: Batteryless sensors; Chipless sensors; Wireless sensors.

1. Introduction

Classical user interface requires a physical contact between the device and the user. It can be, for example, to press a button to switch on an equipment (*e.g.*, a television), or move an equipment to point a location on a plane (*e.g.*, a computer mouse on a screen). In each case, the user interface size depends only on the allowed interactions with the user, which introduce numerous constraints on the device size.

Contactless user interface leverages this limitation by providing a convenient solution to control an electronic device without any assumption on its size. Classical methods are based on computer vision to recognize the gesture of the user, which require direct line of sight between the camera and the user. Thus, even if the size of the equipment is not limited by the user interface, new constraints appear with the camera positioning and field of view... Moreover, since camera modules are fully passive, gesture recognition cannot be done without ambient light.

Radar based sensors, on the other side, can be used for gesture recognition irrespective of the lighting conditions. This approach can allow accurate estimation of movements and real time implementation. However, complex post-processing algorithms have to be realized to detect and classify movements from the received electro-magnetic signals. Several prototypes have already been developed [1,2]. Soli project [1] uses a Frequency Modulated Continuous Wave (FMCW) radar at 60 GHz to detect very subtle signal variations and can produce more than 10000 range-Doppler images per second. These images are then feed to a deep convolutional neural networks to achieve features

34 extraction and classifications of the different gestures. In [2], authors use a similar radar architecture,
35 but process the data using a long recurrent all-convolution neural network.

36 The objective of this paper is to localize accurately an object on a 2D plan without any contact.
37 Localization in 2D can be done with the previously presented solutions however, in both cases, the
38 approaches suffer from the lack of an analytical model to determine accurately and then with low
39 computational effort, the position of the object. Different approaches have been explored to overcome
40 these limitations, for example, in [3] authors have developed a programmable battery-free sensing and
41 computational platform called WISP in which data can be read by a classical RFID reader. The WISP
42 includes an accelerometer which can be used to determine the position of an object from the values
43 produced by the sensor. In this paper, we proposed a new method based on the use of a chipless tag.

44 Chipless RFID technology has been originally design to identify items at a very low cost compared
45 to classical RFID. However, this technology gives the opportunity to use chipless tags beyond their
46 original desings. Indeed, the signal received by the reader carries information which is function of the
47 tag itself (used for identification) but also information which depends on its vicinity that can be used
48 for sensing applications. Moreover, sensing can be realized without limiting the coding capacity of
49 the chipless tag. Sensors based on chipless tags offer contactless, low-cost, and batteryless solutions
50 which can be deployed in real environments. Many researcher have investigated the use of chipless
51 tags to realize sensors for temperature [4–6], humidity [7], gaz detection [8], level of fluids [9] and
52 positioning [10].

53 In this paper, we propose a totally different approach than the ones introduced in [1,2]. Our
54 method is based on the use of chipless tag to provide an analytical model to accurately realize the
55 localization inside the environment and also simplify the post-processing. Since we investigate the
56 problem of 2D localization of an object on which a chipless tag is placed, the problem is equivalent
57 to localize the chipless tag (with the object) in the plane. Moreover, to be robust, the method should
58 work at different heights, and should be insensitive to the other moving objects present inside the
59 environment.

60 Localization based on chipless tags has already been investigated in the literature. The classical
61 method used in [11–14] requires at least three different antennas and estimates the distance between the
62 tag and the known antenna positions with the round-trip time-of-flight. Tri-lateration algorithm is then
63 used to recover the position of a tag from the estimated distances. The classical setup configuration
64 is presented in Fig. 1a. All these approaches use at least 3 different antennas (A_i in Fig. 1a) and have
65 been focused on the structural mode of the tag (*i.e.*, the early part response of the backscattered wave)
66 to determine the tag's position. These approaches could easily be extended to localize the tag in the
67 3D space but remain sensitive to unknown objects present in the environment. In [15], the author has
68 used the phase of the reflected signal to measure distance variations. This method provides a better
69 robustness against the presence of unknown or moving objects in the environment since antenna mode
70 of the response is used, however, displacements are measured along a single direction. Moreover,
71 in [16] authors have determined the location of a chipless tag using the change of the magnitude
72 of the backscattered signal using the information of each of the tag's scatterer. This latter method
73 provides an absolute positioning on a single plane but suffers from a relatively low accuracy. Finally,
74 in [10], authors use phase measurements to localize the tag in a single plan (at a single height) and
75 in a relatively limited area. The approach described in this paper uses the same analytical model
76 than [10,15] but introduces a robust technique to localize the tag at different heights and over a larger
77 area.

78 Our method, presented in Fig. 1b, uses a single antenna A and relies on the phase measurement
79 of the antenna mode of the tag to estimate the distance between the antenna and all the resonators S_i
80 present on the tag. Even if, tri-lateration can be used to localize a tag with only 3 resonators, classical
81 chipless tags are composed of a greater number of resonators. Thus, this approach can easily be
82 extended to localize the tag with a multi-lateration technique to increase the robustness of the results.
83 Moreover, we will see that the selection of the resonators can also be made during the multi-lateration

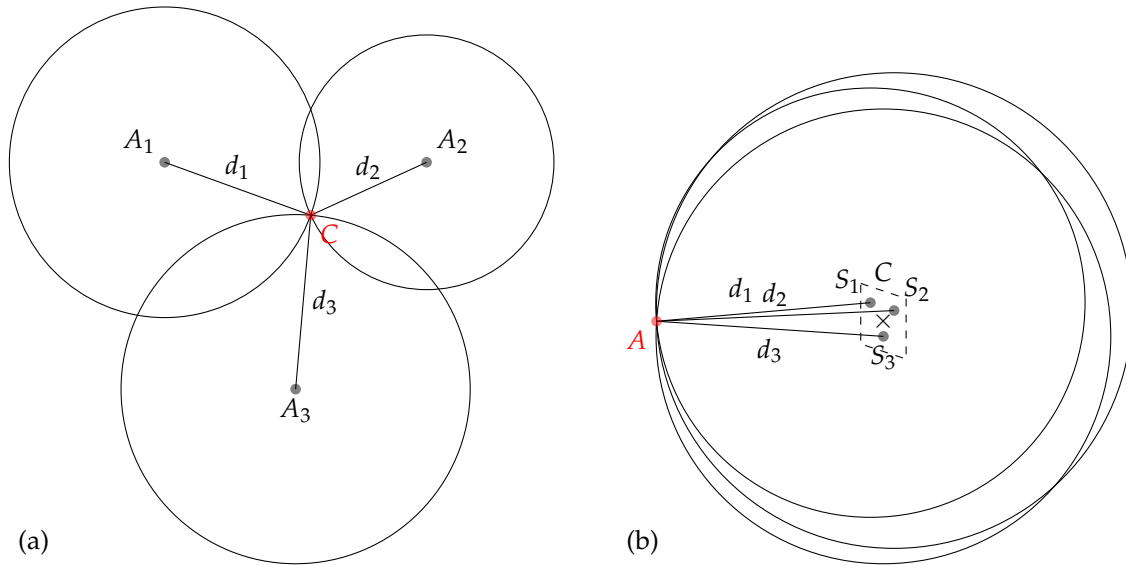


Figure 1. Principle of the multi-lateration used for localization (a) classically used in the literature, (b) proposed in this paper, where A_i are the antennas, C the chipless tag, S_i the scatterers. In both cases antenna positions are known, chipless tag position is unknown.

84 stage to increase the localization area. Our 2D localization method has been applied at different heights
 85 to highlight the performance of the approach. Finally, the presented method permits to localize the tag
 86 on a 2D plan but also does not reduce the coding capacity of the tag since localization uses the same
 87 resonators as the ones used for identification. Thus, classical reading and sensing could be combined
 88 to design new kind of sensors.

89 The paper is organized as follow, in Section 2, we present the RFID chipless technology and we
 90 introduce the analytical model used to determine the distance variation and multi-lateration algorithm
 91 used to localize the chipless tag. Section 3 presents the performance of our approach for distance
 92 determination and localization, at different heights in real environment. Finally, Section 4 concludes
 93 the paper.

94 2. Materials and Methods

95 2.1. Chipless RFID Technology

96 Chipless technology gather multiple different designs and can use different principles. Chipless
 97 tags are usually separated between time domain tags (in which the information is coded in time)
 98 and frequency domain tags (in which the information is coded in frequency). In this paper we
 99 consider a selective frequency tag since these tags provide a relative high coding capacity for a very
 100 compact size [17]. Frequency selective chipless tags are classically composed of several resonators;
 101 each resonator is a simple structure (*e.g.*, short-circuit dipole, C-shape resonator, loop resonator...).
 102 Moreover the resonant frequency associated with each resonator is a function of a simple design
 103 parameter (typically its length). The tag ID is linked to the position in frequency of the different peaks
 104 (or deep) which compose the tag. To realize the reading of a chipless tag, the reader has to be able
 105 to generate an RF power over a large bandwidth (using an harmonic sweep or a UWB pulse) and
 106 to receive the backscatter signal as a function of the frequency to estimate the position of the peaks.
 107 Chipless tag reading is basically based on the magnitude of the received signal. Fig. 2a presents the
 108 classical cross-polarization response of the tag used in this study, in magnitude. The proposed method
 109 to localize a chipless tag is based on the phase of the received signal. Fig. 2b presents for the same tag,
 110 the phase of the backscattered signal as a function of the frequency.

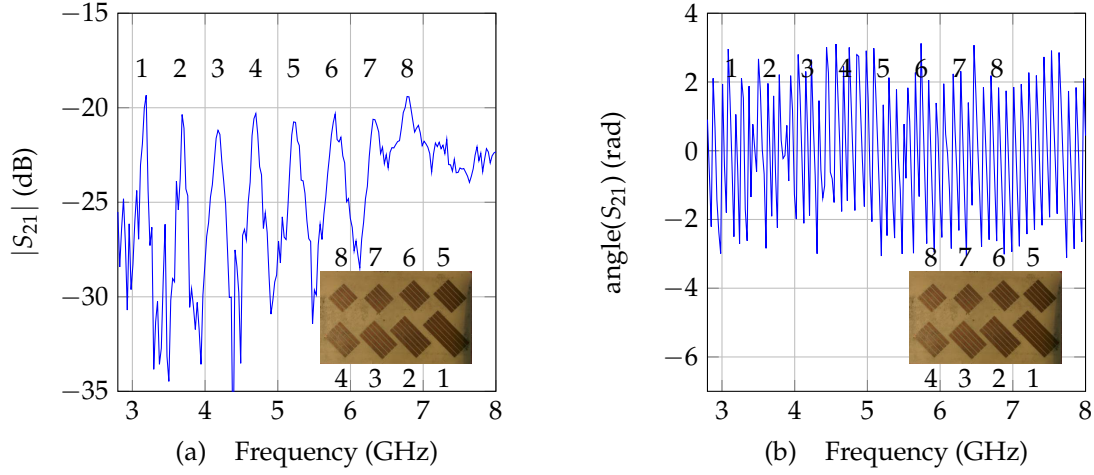


Figure 2. Response of the chipless tag in cross polarization [18] in (a) magnitude and (b) phase as a function of the frequency

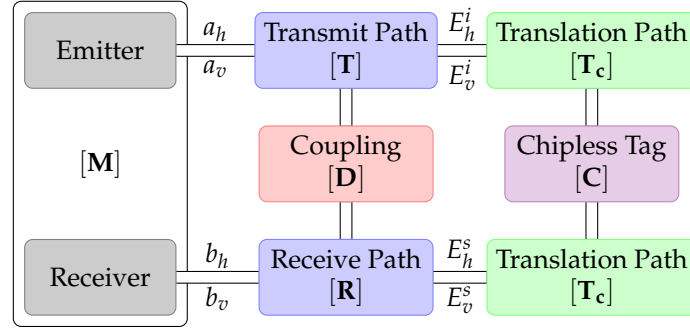


Figure 3. Channel model of the system for displacement measurements with one chipless tag.

111 In Fig. 2a, we can clearly identify the peaks associated with each resonators. Moreover, since our
 112 localization method is based on the phase of the backscattered signal (see Fig.2b), this implies that
 113 localization can be realized without reducing the coding capacity of the tag (the same resonators can
 114 be used for reading and sensing). The next sections present the method used to determine the distance
 115 between the tag and the antenna, and to localize the chipless tag.

116 2.2. Distance determination

The model of the transmission between the reader and the chipless tag [15] is presented in Fig. 3. The detection system is represented by the block \mathbf{M} . Blocks \mathbf{T} and \mathbf{R} represent respectively the transmitting and the receiving path. Coupling between emitting and receiving antenna is noted \mathbf{D} and block \mathbf{C} represents the chipless tag. Since the tag can be located at a given distance d form the antenna, blocks \mathbf{T}_c represent the phase offset due to propagation and is equal to:

$$\mathbf{T}_c = \begin{bmatrix} e^{-jkd} & 0 \\ 0 & e^{-jkd} \end{bmatrix} \quad (1)$$

where d is the distance between the tag and the antenna. From this model, one can extract the signal received in cross-polarization at two different positions d_0 and d_1 :

$$\begin{cases} M'_{vh}(d_0) = I_{vh} + T_{hh}C_{vh}e^{-j2kd_0}R_{vv} \\ M'_{vh}(d_1) = I_{vh} + T_{hh}C_{vh}e^{-j2kd_1}R_{vv} \end{cases} \quad (2)$$

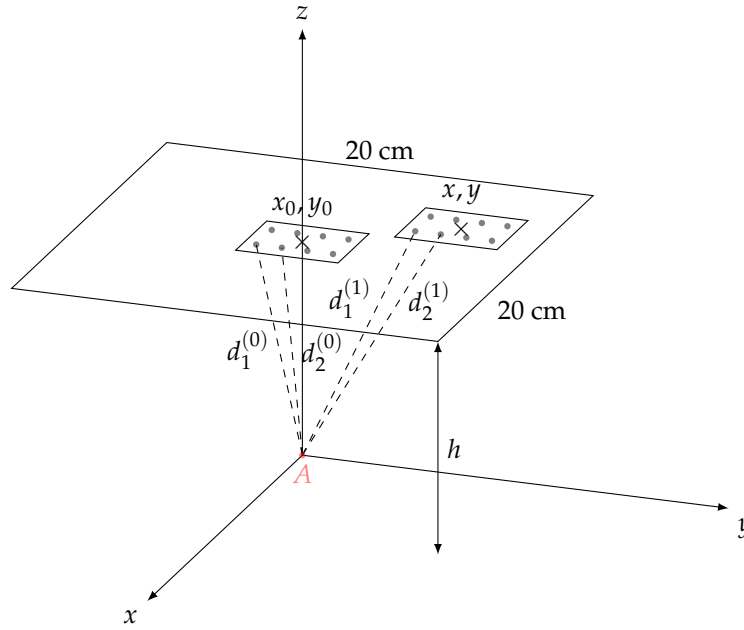


Figure 4. Architecture of the configuration used for localization showing the reference position x_0, y_0 and an unknown position x, y

117 where I_{vh} is the direct coupling between antennas, also called isolation measurement.

From (2), a distance variation Δd can thus be extracted by using only 2 measurements $M'_{vh}{}^{d^{(0)}}$ and $M'_{vh}{}^{d^{(1)}}$ at 2 different locations $d^{(0)}$ and $d^{(1)}$, and a background measurement I_{vh} . Distance variation $d^{(1)} - d^{(0)}$ can thus be extracted and is equal to:

$$\Delta d = d^{(1)} - d^{(0)} = -\frac{1}{2k} \text{angle} \left(\frac{M'_{vh}{}^{d^{(1)}} - I_{vh}}{M'_{vh}{}^{d^{(0)}} - I_{vh}} \right) \quad (3)$$

118 Note that this equation holds in cross-polarisation and only at a resonant frequency since at other
119 frequencies, reflections from the environment could be higher than the response of the tag.

120 An unknown distance (e.g. $d^{(1)}$) can thus be determined if the other distance is known (e.g. $d^{(0)}$)
121 and assuming a displacement $|d^{(1)} - d^{(0)}| < \lambda$. Details can be found in Fig. 4. Finally, if the tag contains
122 more than one resonator, the distances can also be determined independently for each resonator. In
123 the following the position in which distances are known is called the reference position.

124 2.3. Localization

125 As the relative positions between resonators are known (see Fig. 2), and distances between
126 resonators and the antenna can be extracted with the previously described method, it is possible to
127 localize the tag using multi-lateration algorithms (as shown in Fig 1b) if at least three distances and the
128 antenna position are known. Solutions based on Gauss-Newton methods have been developed in [19]
129 and [20] but remain relatively complex and assume additive white gaussian noise on the estimated
130 distances. In this paper, we consider a simpler and robust optimization process to minimize the square
131 error between the estimated distances (obtained form measurements) and the distances obtained form
132 a candidate solution. Details of the procedure are given in Section 3. The following section describes
133 the measurement bench used to localize a chipless tag.

134 2.4. Measurement Bench

135 The measurement bench used in our study for chipless tag localization is presented Fig. 5. The
136 chipless tag is placed at the end of a plastic arm which can move along the three dimensions x, y and

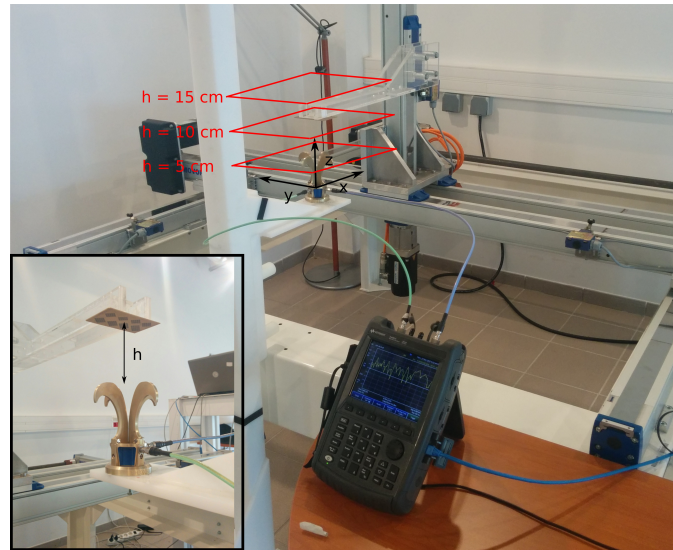


Figure 5. Measurement bench in real environment used for localization

137 z. The Satimo QH2000, which is two-port antenna used to measure the signal in both vertical and
 138 horizontal polarization, is fixed and located under the tag. This antenna is connected to port 1 and 2 of
 139 the VNA. Cross-polarization response of the tag corresponds to the S_{21} parameter and is acquired over
 140 the bandwidth 2.8 – 8 GHz. Response of the tag is measured and stored for each position in a square of
 141 20 cm side (with a 1 cm step along x and y) above the antenna and for three different heights h which
 142 are 5 cm, 10 cm and 15 cm (see Fig. 5). All the measurements has been realized in real environment.

143 3. Results and Discussions

144 3.1. Performance of distance determination

145 Distances estimation $d_i^{(1)}$ is obtained by adding the distance of the reference position $d_i^{(0)}$ and the
 146 distance variation Δd obtained with (3) which uses the phase difference between the two positions.
 147 In the following, reference position has been set to $x_0 = 0$, $y_0 = 0$, and a height of $h = \{5, 10, 15\}$
 148 cm from the antenna. Moreover, since the phase belongs to the interval $[-\pi; +\pi]$, for displacement
 149 greater than the wavelength, phase difference is not proportional to the displacement. To estimate
 150 the correct phase value for displacement greater than the wavelength, phase need to be unwrapped.
 151 This operation consists to add multiples values of $\pm\pi$ to the original phase to avoid any phase shift.
 152 Even if this process can easily be applied for 1D signal, phase unwrapping for 2D signal is a complex
 153 task since modification of the phase has to be done jointly along x and y . In this work, we have used
 154 the algorithm developed in [21] to unwrap the phase in 2D. Fig. 6 presents the unwrapped phase for
 155 all the resonators of the tag presented in Fig. 5. We can see that the unwrapping process produces
 156 a smooth phase variation along x and y , however, for some areas, we can clearly observe important
 157 phase shift due to error during the unwrapping process (top left corner in Fig. 6a and top right corner
 158 in Fig. 6h) due to a low signal to noise ratio. Results produced with multi-lateration algorithm will be
 159 affected by these erroneous distances.

160 Estimation of the distance can be realized using the unwrapped phase obtained previously and (3).
 161 Fig. 7 presents the evolution of the distance for all the resonators when the chipless tag is moved
 162 along x and y . We can note that all curves intersect at $(0, 0)$ since this position has been chosen as the
 163 reference position x_0 , y_0 (where phase difference is equal to 0). Moreover, in Fig 7a, from the reference
 164 position, we can see that when x increases (tag moving to the right), distances for resonators 5, 6, 7
 165 and 8 and the antenna increase, for resonators 1, 2, 3 and 4, distances decrease and then increase since
 166 these resonators are located on the other side of reference position. Same observations can be extracted

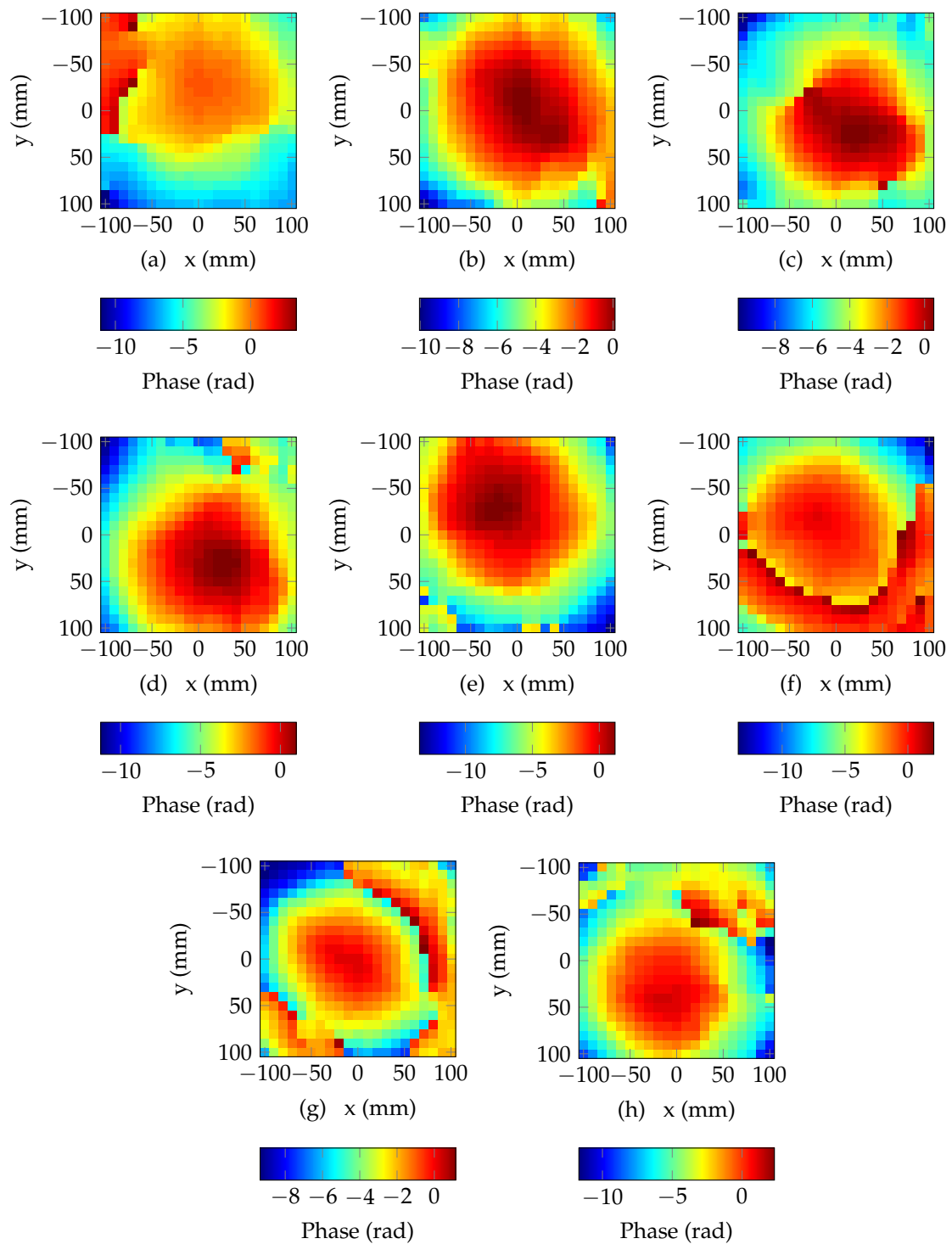


Figure 6. Unwrapped phase as a function of the position on the plan, (a) for the 1st (3.19 GHz), (b) for the 2nd (3.68 GHz), (c) for the 3rd (4.18 GHz), (d) for the 4th (4.70 GHz), (e) for the 5th (5.22 GHz), (f) for the 6th (5.79 GHz), (g) for the 7th (6.33 GHz), (h) for the 8th resonant frequency (6.78 GHz) for the reference position $x_0 = 0$, $y_0 = 0$ and at a height of $h = 10$ cm from the antenna.

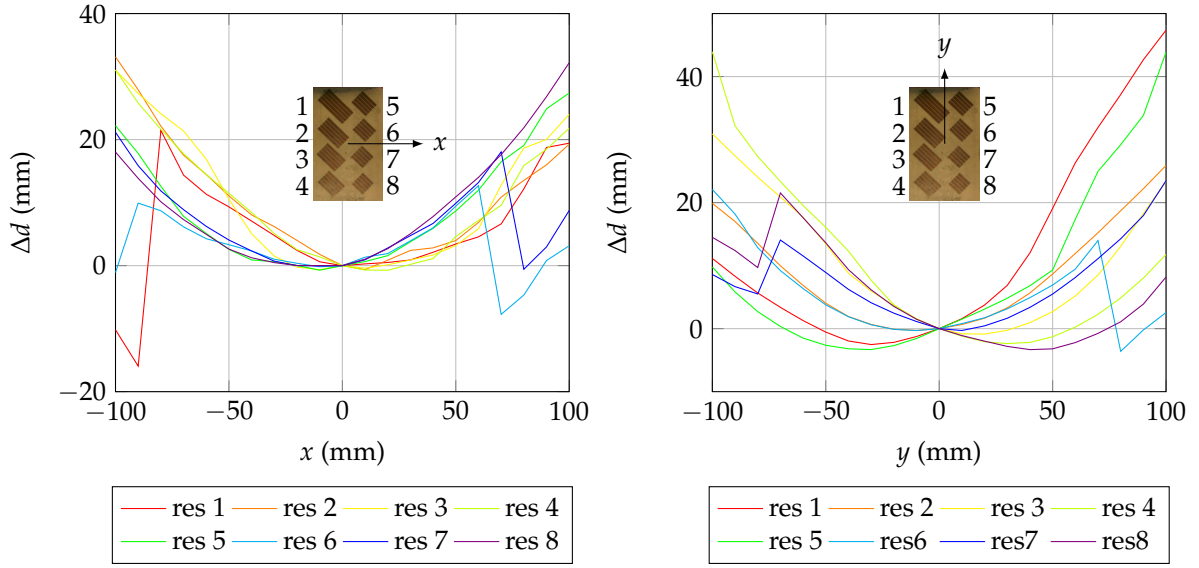


Figure 7. Estimation of the distance variations for the 8 resonators as a function of a displacement for a reference position located at $x_0 = 0$, $y_0 = 0$ and at a height of $h = 10$ cm along (a) x and (b) y .

167 from Fig. 7b. Finally, for some resonators, (resonators 1, 6 and 7 in Fig. 7a and resonators 6, 7 and 8 in
 168 Fig. 7b), we can observe the effect of unwrapping errors since distances undergo sudden changes of 1
 169 wavelength. Since λ is shorter for high resonant frequency, the unwrapping error value is smaller for
 170 these resonators (but can appear more often for the same displacements).

171 3.2. Performance of localization determination

Multi-lateration can be used to determine the position on the 2D plan from the distances d_i between the antenna and each resonators. The objective of the multi-lateration is to solve a system of eight equations:

$$\begin{cases} \hat{d}_1 = \sqrt{(x + x_1 - x_A)^2 + (y + y_1 - y_A)^2 + (z + z_1 - z_A)^2} \\ \hat{d}_2 = \sqrt{(x + x_2 - x_A)^2 + (y + y_2 - y_A)^2 + (z + z_2 - z_A)^2} \\ \vdots \\ \hat{d}_8 = \sqrt{(x + x_8 - x_A)^2 + (y + y_8 - y_A)^2 + (z + z_8 - z_A)^2} \end{cases} \quad (4)$$

where x_A , y_A and z_A , are the coordinates of the antenna and x_i , y_i and z_i are the coordinates of the resonators at the reference position (see Fig. 4). The objective is to determine x and y where \hat{d}_i is the estimated distance between antenna and resonator i obtained by measurement (as previously described). Classical resolutions are based on Gauss-Newton methods. Unfortunately, as we have seen, the distances estimated using phase measurement are subjected to errors due to phase unwrapping. Each time an error appears during the unwrapping process, a distance of $\pm\lambda$ is added to the distance variation of one resonator. To tackle this problem, we consider, as a first approach, a simpler minimization of the square error:

$$\langle \hat{x}, \hat{y} \rangle = \arg \min \sum_{i=1}^8 (\hat{d}_i - d_{ci})^2 \quad (5)$$

172 where d_{ci} is the distance between the antenna and resonator i obtained with a candidate solution
 173 of coordinates x_c, y_c . Minimization is realized iteratively using a random search over the set of all
 174 possible x and y coordinates. The algorithm start by computing the distances d_{ci} obtained between

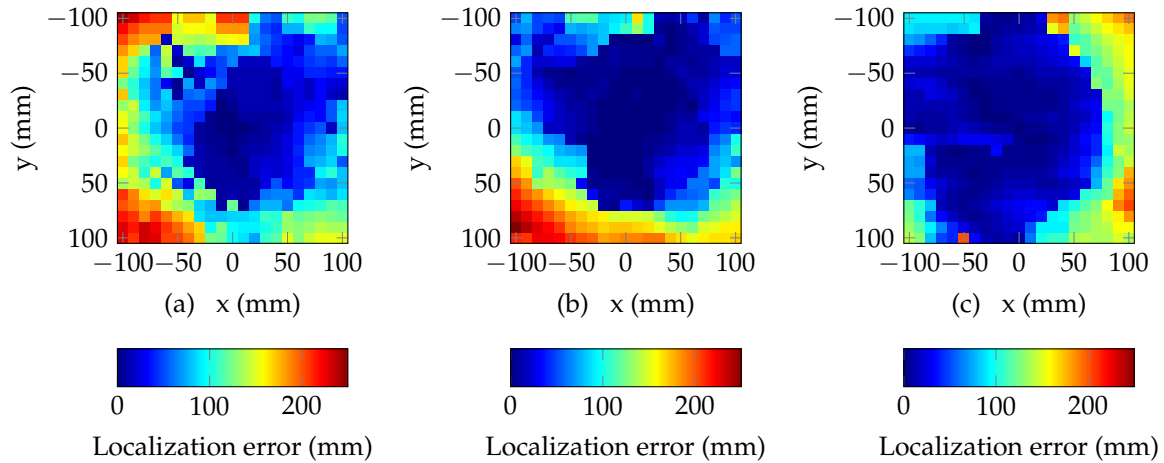


Figure 8. Localization error in mm of the multi-literation algorithm using 8 resonators for (a) $d = 5$ cm, (b) $d = 10$ cm and (c) $d = 15$ cm.

175 the antenna and an initial position and its corresponding square error with the estimated distances,
 176 then, a perturbation (following a gaussian distribution) on x and y is added on this initial position
 177 and the new square error is estimated. If the new position has a smaller square error than the one
 178 corresponding to the actual iteration, this new position is then used in the next iteration. In the other
 179 case, a new perturbation is added to the actual candidate position. Thus, the algorithm iteratively
 180 converges toward the estimated position \hat{x}, \hat{y} . Also, it is important to notice that this algorithm uses all
 181 the resonators of the chipless tag (as we have seen in Fig. 1 a minimal number of 3 distances is required
 182 to estimate the position of the tag).

183 Figure 8 presents the performance of the multi-literation algorithm using random search. The
 184 plots present the error in magnitude between the estimated position (returned by the algorithm) and
 185 the true values x, y of the tag location (known using the positioning table, see Fig. 5), for each position.
 186 Figure 8a, 8b and 8c plot the results corresponding to heights h of 5 cm, 10 cm and 15 cm. For all
 187 positions, initial position has been set at $x = 0$ and $y = 0$. The algorithm has been run over 2000
 188 iterations which ensures the convergence (*i.e.*, 10 ms). We can see that multi-literation algorithm
 189 returns an accurate estimation of the location over a large part of the overall space (areas in blue in
 190 Fig. 8). If we consider a reduced an area of 10 cm centered above the antenna, localization error is lower
 191 than 1.98 cm (resp. 1.00 cm and 0.941 cm) for a distance of 5 cm (resp. 10 cm and 15 cm). Moreover, we
 192 can easily see that the area where the localization error is low, increases when the distance between
 193 the tag and the antenna increases. These results constitute the basic performances of our localization
 194 method and will be used as a reference for comparison purpose with the performances with the
 195 method presented in the next section.

196 3.3. Selection of a subset of resonators

197 From the results presented in Fig. 8, the accuracy of the proposed method is good in an area
 198 located above the antenna. However, as the distance between the tag position and the reference position
 199 increases, the accuracy becomes lower due to the phase unwrapping error which add (or subtract) a
 200 quantity equal to one wavelength in case of measurement noise for some resonators. To improve the
 201 performances of our solution, we propose to select a subset of resonators to exclude the ones subjected
 202 to phase unwrapping errors (a minimum of three resonators is required). Since these resonators could
 203 not be identified during the optimization, we propose to estimate the mean square error for each
 204 combination of resonators. Minimization is realized considering all the possible combinations. Note
 205 that the number of combinations increases rapidly a subset of resonator is considered which directly
 206 affects the execution time.

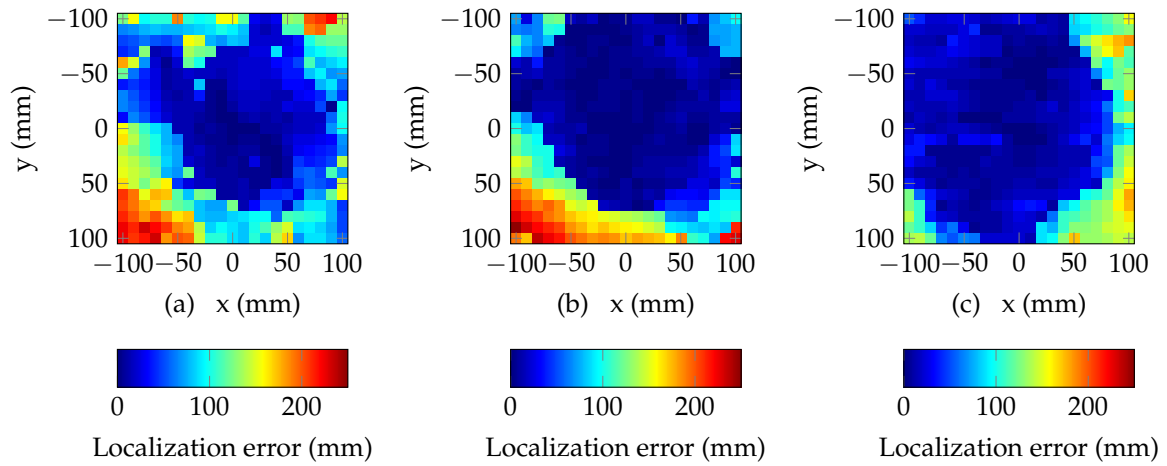


Figure 9. Performance of the multi-literation algorithm using 7 resonators for (a) $d = 5$ cm, (b) $d = 10$ cm and (c) $d = 15$ cm.

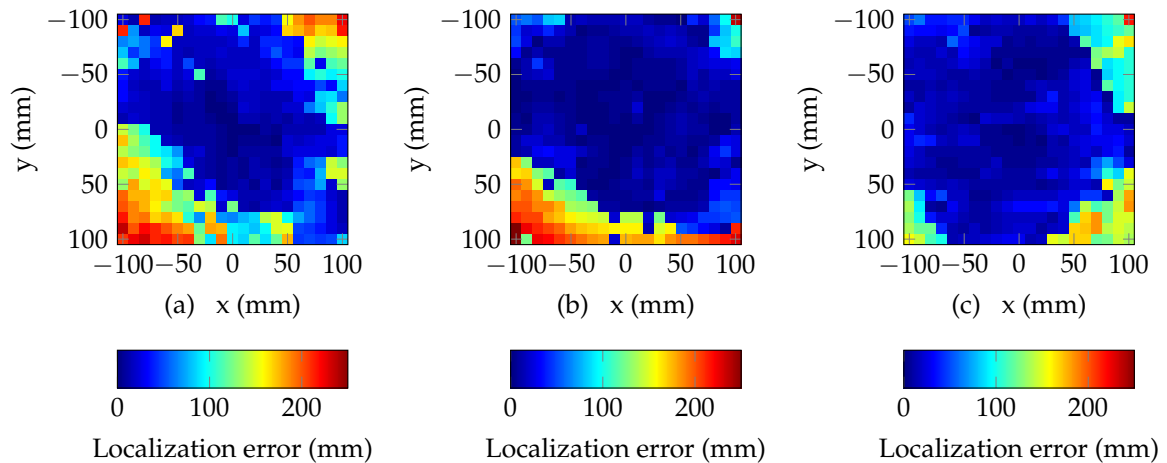


Figure 10. Performance of the multi-literation algorithm using 6 resonators for (a) $d = 5$ cm, (b) $d = 10$ cm and (c) $d = 15$ cm.

Table 1. Proportion of the total area (20 cm × 20 cm) where the localization error is less than 50 mm

	$d = 5$ cm	$d = 10$ cm	$d = 15$ cm
8 resonators	38.8%	57.1%	65.5%
7 resonators	48.8%	68.3%	73.7%
6 resonators	61.7%	78.9%	80.3%
5 resonators	66.4%	84.6%	80.0%
4 resonators	59.6%	78.0%	78.7%
3 resonators	45.6%	63.7%	68.7%

207 Fig. 9 and 10 present the results of the selection of a subset of resonators. We can see that the
 208 selection of a subset of different resonators based on the minimization of the mean square error can
 209 effectively increase the size of the localization area without reducing the overall accuracy. Moreover,
 210 this method permits to increase the performances of the multi-iteration algorithm for all the presented
 211 distances. Results are summarized in Table 1 where the proportion of total area where the error
 212 is less than 50 mm, is determined for different subsets and distances. We can see that the proposed
 213 method permits to increase the localization area. In average, this area can be increased by a factor
 214 higher than 20% by considering a subset of five resonators.

215 4. Conclusion

216 In this paper we have shown that we can successfully localize a chipless tag using phase
 217 measurement over a significant area and at different heights. Distance estimation has been obtained
 218 using phase difference between two positions. Accuracy of the proposed method is higher than 2 mm
 219 but remains sensitive phase unwrapping errors for displacement longer than one wavelength. Selection
 220 of resonators has been proposed to overcome this limitation. Final results show that a localization
 221 error less than 1 cm can be achieved in a square of 10 cm side located above the antenna. Finally, this
 222 robust localization can be realized without reducing the coding capacity since the same resonators are
 223 used for classical reading (based on magnitude) and sensing (based on phase). Finally, this method can
 224 easily be extended to determine 3D positioning and/or orientation to provide a wireless, batteryless,
 225 printable, possibly disposable and very low-cost positioning system.

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