SAW RFID Tag Spatial Division Multiple Access
Based on 3D Reflector Response Localization
Using a Wideband Holographic Approach

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ABSTRACT  Surface acoustic wave (SAW) radio-frequency identification (RFID) has high potential for industrial applications, where automated identification and localization of assets represent the backbone of process controlling and logistics. However, in situations where multiple tags are simultaneously interrogated, the response patterns corresponding to the hard-coded reflectors are prone to overlap, preventing their association with the corresponding tags and, hence, the correct tag decoding. Identification and localization of multiple SAW RFID tags are addressed in this work under this challenging effect, known as collision, with a multi-antenna mobile robot-based synthetic aperture approach. Using the estimation of the spatial probability density functions of the SAW tag reflectors over a given interrogation aperture, the received impulse responses can be resolved in three dimensions and clustered with respect to their estimated locations. The performance of the proposed approach to associate and localize the signals from multiple tags was evaluated theoretically and experimentally.

INDEX TERMS  3D localization, anti-collision, RFID, SAW, SDMA.

I. INTRODUCTION

Automated high-volume asset identification and localization solutions based on radio-frequency identification (RFID) are highly required within a digitalization context driven by the evolution of the Industrial Internet of Things, leading to a higher efficiency when monitoring industrial processes while enabling managing and tracking operations in real time. However, some industrial environments have particular challenges, which may reduce the performance of some systems or even can prevent their implementation for industrial processes involving harsh conditions such as high temperatures, humidity, or strong multipath effects.

Surface acoustic wave (SAW) RFID technology offers a robust solution under such extreme environmental conditions while, on top, there are no maintenance costs, as these tags’ working principle is completely passive. This technology is characterized by a low-latency link, and it has a large coding capacity suitable for commercial applications [1]. Also, SAW tags can even be used on metal objects [2], and they can also achieve considerable penetration into challenging structures such as pallets containing metal or liquid items [3].

In contrast to other technologies such as integrated circuit (IC) based RFID, SAW tags cannot be selectively interrogated since all tags within the interrogation field of view will respond simultaneously, generating potential overlap of the signal responses, which reduces or even prevents correct tag evaluation. Therefore, new algorithms and decoding schemes are presented in this paper to effectively decode SAW RFID signals. Furthermore, for the first time, this implemented new SAW tag spatial diversity multiple access (SDMA) functionality enables the parallel localization of several tags, which is a crucial feature for tracking these assets within, for example, a warehouse, in addition to the identification of the labeled objects.

In this work, multiple SAW tag identification and localization are investigated using a wideband holographic
reconstruction approach based on synthetic aperture radar to unveil the potential of this technology for identification and high accuracy localization in three dimensions for almost every asset application, enabling a new solution that can operate even under harsh industrial conditions. While the simultaneous interrogation and localization of multiple SAW tags are solved, this novel approach also suppresses multipath distortions, which are always present in industrial environments.

In the next section, a description of SAW RFID tag fundamentals, as well as a review of tag identification principles and anti-collision techniques, is presented. In Section III, the interrogation approach and the algorithm development for three-dimensional (3D) localization of SAW signals that has been implemented in this work are explained. In Sections IV and V, the setup used for the experiments is presented and the obtained results are shown, respectively. Finally, in Section VI, conclusions and outlook perspectives are discussed.

II. SAW RFID CODING AND MULTIPLE ACCESS TECHNIQUES

RFID can be achieved based on the working principle of reflective SAW delay lines. The smart design of SAW devices allows implementation of efficient coding schemes based on the backpropagated signal characteristics. Also, interrogation techniques can be applied to add a diversity gain, especially for multiple tag access situations. These concepts, together with a discussion regarding their limitations, are described next.

A. SAW RFID WORKING PRINCIPLE

A delay-line-based SAW RFID tag consists of a piezoelectric substrate with an antenna connected to a periodic set of metallic structures, known as an interdigital transducer (IDT), and a set of reflector structures located at different separations with respect to the IDT. When an electromagnetic radio-frequency (RF) wave is received by the antenna, a mechanical SAW is stimulated on the IDT, which is propagated over the substrate surface. The SAW is partially reflected back at each reflector, which generates a time-coded pattern that is unique for each combination of reflectors. At the IDT, the SAW produces an electric charge distribution generating an electrical signal at its terminals. This signal is reconverted into RF waves, which are eventually radiated from the tag antenna to the interrogation unit with a delay determined by the individual round-trip propagation paths at each reflector.

The complete propagation path is defined by the sum of the distance between the interrogation unit and the SAW tag plus the distance from the IDT to the reflectors. The characteristics of the received signals will, therefore, be dependent on the location of the tag with respect to the interrogation element and the reflector configuration.

B. REFLECTOR-BASED CODING SCHEMES

To decode the tag ID, the round-trip delays of the reflected SAW signals must be estimated. The combination of reflector responses results in a signal pattern corresponding to an identification code, which is defined based on the signal characteristics, such as power and phase. Using certain geometrical configurations and reflector designs, efficient types of modulation schemes can be implemented to transmit unambiguous identification codes within the response signal. Many coding strategies have been investigated to design reflector schemes that are able to unambiguously associate signal responses with unique identification numbers.

Based on a threshold power detection on a pulse position grid, an on–off keying (OOK) scheme can be defined by the presence or absence of reflectors at predetermined time slots, which can be associated with digits or symbols. Although this scheme can be implemented and decoded with low complexity, it requires a large number of reflectors to achieve commercial data capacities.

An alternative coding scheme based on encoding the reflectors at specific slots defined within a code grid is widely known as pulse position coding (PPC). This coding technique is widely implemented for SAW identification due to its robustness and relatively high data capacity. The delay range where the $P$ code reflector signals of the SAW tag are expected to be estimated can be divided into different coding position groups, each with $N$ slots defined by a specific width, as depicted in Fig. 1. This width is limited by the system resolution and can be estimated using the Cramér-Rao lower bound, which mainly depends on the bandwidth, the number of sampled points, and the signal-to-noise ratio (SNR) [4].

In each group of slots, only one “on” reflector impulse response is expected, and its position contains the information corresponding to a given symbol. Thus, several symbols can be encoded using a single reflector, while the combination of all reflectors defines the identification code of the tag. As a result, $N^P$ codes can be implemented using this scheme, offering more data capacity than OOK using fewer reflectors, which is also an advantage regarding the required SNR for correct decoding, since the reflected signal can be distributed through fewer reflectors [5].

A different coding scheme based on signal phase estimation of the reflectors is applied by phase coding. This coding technique is implemented by accurate slight position shifts of the reflector positions according to a defined set of values.
corresponding to given symbols. The position shifts are usually defined by distances inversely proportional to the carrier wavelength used by the interrogation signal. Although this alternative offers a higher code capacity than PPC, a higher SNR is also required to correctly decode the tags, which practically corresponds to a reduction of the reading range. A study of the maximum information content contained in SAW RFID tags using different modulation schemes based on the Shannon–Hartley theorem analyzed over the reading range is presented in [6].

**C. MULTIPLE SAW TAG EVALUATION**

When multiple SAW tags are located within an interrogation field of view, the backscattered response patterns are superposed and, therefore, reflector evaluation may be unambiguous. This is especially critical when the use of reference reflectors is introduced for calibration purposes since their interaction may lead to systematic interference. Tag collision can prevent correct decoding and the association of reflector signals with their corresponding source tags. The more the SAW tags used within a limited space, the higher the probability of potential collisions. Therefore, anti-collision methods for SAW RFID are required to enable multiple tag access. A diversity of methods have been investigated [7], including different interrogation techniques and reflector configurations.

Time-division multiple access (TDMA) can be implemented using tags coded over non-overlapping substrate segments, splitting the estimation delay region between the expected tags to be evaluated, as shown in [8]. This approach has, however, a limited practical use since the more the tags to be evaluated, the smaller the splitting regions for each tag to unambiguously associate the different responses, besides the additional propagation losses and material costs that will result.

Based on information theory, code-division multiple access techniques can be applied, such as the use of linear block codes proposed in [9], which achieve a higher code capacity than TDMA approaches. However, the number of tags that can be simultaneously evaluated might be limited for some applications. In addition, spread spectrum tag anti-collision based on orthogonal frequency codes has been proposed in [10], using a special device design that allows encoding the signals over the interrogation bandwidth. This technique requires a wide bandwidth spread spectrum signal, which in industrial scenarios is limited by industrial, scientific and medical band (ISM) regulations. More recently, an encoding technique is proposed in [11], which combines time and frequency coding schemes to increase anti-collision combinations of SAW RFID signals.

Spatial diversity approaches to extend the number of readable tags and improve readout reliability have also been investigated for SAW RFID evaluation. Hartmann and Claiborne [12] proposed the use of spatial discrimination based on selective antenna patterns to narrow the number of simultaneous responses that might be evaluated in a readout, focusing the interrogation beam within a defined space. This approach is very attractive since it only requires a single-channel unit, but it also requires a special antenna design and fulfills certain use case conditions. Other approaches applying static multichannel concepts have been proposed in [13] and [14] based on the angle of arrival estimation between interrogation elements, which allows tracing the interference effects between reflector responses and separate SAW tag signals over their phase difference. These techniques can be extended taking advantage of situations involving moving tags or moving interrogation antennas since an additional spatial diversity gain can be added with coherent superposition of measurements over multiple locations. This is especially interesting when applied on SAW RFID, as potential collisions due to reflector-based interrogation can be resolved, while the association of reflectors can then be reconstructed based on the estimated spatial information. Thus, this enables multiple access decoding even for identical codes as long as the tags are placed in different spatial resolution cells. The size of the resolution cell is determined by (7) and (8), which are presented in Section III. Also, the influence of multipath on the localization accuracy is suppressed, and, on top of that, the localization properties can be enhanced in a way that can be practically implemented and adapted to conventional commercial situations.

**III. SIGNAL MODELING AND ALGORITHM DESIGN**

A mathematical model is presented to describe the physical dependency between the SAW tag signal characteristics and their spatial location in relation to a reference transceiver or interrogation unit considering a frequency-modulated continuous-wave (FMCW) interrogation for the calculations without loss of generality. Further interrogation approaches for SAW devices can be found in [15].

**A. SAW RFID SIGNAL MODELING**

The main physical contributions defining the round trip delay (RTD) of the signals consist of the free space propagation delay \( \tau_0 \), dependent on the distance \( d_{m,k} \) between interrogation element \( m \) and SAW tag \( k \), and the acoustic propagation delay \( \tau_{SAW,p} \) defined by the coded reflector positions \( r_p \) relative to the IDT,

\[
\tau_{RTD} = \tau_0 + \tau_{SAW,p} = 2 \left( \frac{|d_{m,k}|}{c_0} + \frac{r_p}{c_{SAW}} \right). \tag{1}
\]

Since \( c_0 \) is about five orders of magnitude larger than SAW propagation velocity \( c_{SAW} \) [16], \( \tau_{SAW} \) represents the dominant contribution to the RTD.

After baseband conversion, intermediate frequency components \( f_p \) can be extracted corresponding to each reflector response proportional to their RTD by the interrogation bandwidth \( B \) and the sweep duration \( T \), as described in (2):

\[
f_p = \frac{B}{T} \cdot \tau_{RTD}. \tag{2}
\]

The \( \tau_{RTD} \) is also contained in the phase of the signal reflections, which is inversely proportional to the carrier wavelength.
of the interrogation signal \( (\lambda_c) \),
\[
\varphi_p = \frac{2\pi \cdot c_0}{\lambda_c} \cdot \tau_{RTD}.
\] (3)

Although both reflector frequency and phase are dependent on the RTD as described, these estimators offer different variance as described in [4]. Considering an interrogation unit working at the 2.4-GHz ISM band with a bandwidth of 83.5 MHz, based on the Cramér–Rao lower bound, the variance using phase estimation is several times lower than using frequency:
\[
\frac{\text{var} \{ \hat{r}_{SAW,p} \}}{\text{var} \{ \hat{r}_{SAW,p} \}} = \frac{B^2}{3f_c^2} \approx \frac{1}{2500}.
\] (4)

Based on these mathematical relations, the analytical discrete model of a SAW tag signal can be described as a linear combination of the reflector responses \( P \),
\[
s_k(t) = \sum_{p=1}^{P} A_p \cdot e^{j(2\pi f_p + \varphi_p)} + w(t),
\] (5)
where \( A_p \) depicts the corresponding reflector signal amplitude, \( P \) is the total number of reflectors, and \( w(t) \) represents the measurement noise.

When evaluating multiple tags, reflector responses coded at equal or even near substrate positions \( r_p \) might not be resolved due to the limited interrogation bandwidth. This interaction generates interference effects according to the phase differences, which eventually can reduce reflector amplitudes below the detection threshold. Nevertheless, the unique free space delay contribution of each reflector can be exploited to reconstruct reflector signals.

**B. SPATIAL REFLECTOR SIGNAL RECONSTRUCTION**

The proposed localization and SDMA concept is based on a transponder localization technique that was introduced for wireless positioning systems and for ultra-high frequency (UHF) RFID tag localization [17], [18]. These concepts are now extended for SAW tags.

Considering an arbitrary interrogation element \( m \) and a SAW tag \( k \) located in three dimensions over a Cartesian space \( r = (x, y, z) \), the distance between the elements can be calculated based on the Euclidean norm \( \| \cdot \|_2 \) as depicted in (6):
\[
d_{m,k} = \| r_m - r_k \|_2.
\] (6)

A detected set of signal responses backscattered from a SAW tag will share a common free space contribution, while each individual reflector will have its own acoustic delay, which is, in the following, considered an initial offset that can be calibrated under the assumption of no physical conditions modulating the tag during the measurement. This information can be iteratively collected along the relative movement between tag and interrogation element, generating a synthetic aperture.

Along the aperture dimension, the lateral resolution is defined by the aperture length \( D \), the carrier wavelength, and the separation \( R_0 \) between the aperture plane and the tag,
\[
\delta_{\text{lat}} \approx R_0 \cdot \frac{\lambda_c}{D},
\] (7)
assuming that the antenna beam width captures the region where the tags are located along all aperture positions. Besides, the radial resolution can be defined as shown in (8):
\[
\delta_{\text{rad}} \approx \frac{R_0}{D}.
\] (8)

Based on the Cartesian space where the tags are located, hypothesis signals \( s_{H_{m,r}} \) can be simulated along a set of spatial grid positions \( r \),
\[
s_{H_{m,r}} = e^{i\varphi_{H_{m,r}}},
\] (9)
where the phase hypothesis can be defined using the interrogation system carrier wavelength \( \lambda_c \) and the assumed distance \( d_{m,r} \) according to (10):
\[
\varphi_{H_{m,r}} = \frac{4\pi \cdot d_{m,r}}{\lambda_c}.
\] (10)

Considering that signal responses are backscattered from unknown tag sources, they are, in the following, indexed as \( i \) since they can contain one or more reflector contributions \( p \). Each signal response evaluated at a specific spatial location \( n \) can be correlated with a set of simulated signals \( s_{H_{m,r}} \) over the search grid, using the mathematical relation (11),
\[
C_{n,i}(r) = \frac{1}{M} \sum_{m=1}^{M} e^{j(\varphi_{H_{m,r}})} \cdot A_{m,n} \cdot e^{-j(\varphi_i)},
\] (11)
where \( C_{n,i}(r) \) is the correlation between the \( n \) measured signal response and the simulated signal at position \( r \) after combining the responses from the \( M \) antenna elements. The amplitude of the signal responses is set to 1 since they are more sensitive to multipath interferences [19].

Performing a coherent superposition of \( C_{n,i}(r) \) over \( N \) measurements along the synthetic aperture, a spatial probability density function \( f_i \) corresponding to each detected signal over the defined Cartesian map can be estimated using (12),
\[
f_i(x, y, z) = f(\tau) = \frac{1}{N} \left| \sum_{n=1}^{N} C_{n,i}(\tau) \right|,
\] (12)
where the hypotheses of each signal location are represented with a probability weight. A high probability for a given position is expected when the correlation for a specific location is iteratively high along different aperture measurements. In the same way, multipath reflections and other measurement distortions, which differ over the interrogation positions, are expected to sum up incoherently, resulting in lower probability values.

If multiple reflector contributions from different tag locations are contained within a single received impulse response, multiple modes on the spatial probability density function (PDF) are expected with specific maxima, which correspond to the most likely positions of the source tags in the relative
interrogation coordinate system. Then, reflector association can be performed based on the estimated spatial mapping, as represented in Fig. 2.

IV. EXPERIMENTAL SETUP

To evaluate the proposed anti-collision approach, an experimental setup was prepared with multiple tags located in an indoor environment with strong multipath conditions, where the contributions scattering from the surrounding objects together with the signals generate an additional challenge for the system performance, as commonly found in industrial environments. The evaluated SAW tags used pulse position coding with 16-bit identification codes embedded in four reflector responses in addition to two calibration reflectors corresponding to the start and stop digits, which are encoded at a defined acoustic distance from the IDT and, thus, are expected to collide when measured with other tags simultaneously. Different tags were placed on plastic boxes at known positions for evaluation purposes as shown in Fig. 3.

The SAW tags were interrogated with a linear FMCW scheme within the 2.4-GHz ISM band, using a ramp duration of 100 μs and a frequency bandwidth of 83.5 MHz. A uniform linear array (ULA) consisting of four transceiver antennas was mounted on the mobile robot platform, where the inter antenna spacing was a carrier wavelength $\lambda_c$ between elements. The reader was integrated into a mobile robot unit, which drove on a given linear trajectory in parallel to the tag matrix. Two consecutive measurements have been taken within a sampling interval of $\lambda_c/4$ to fulfill the spatial sampling theorem in the driving direction.

The position of the robot was given by the robot’s odometry data. Using reference markers on the floor, slight convex curves were observed instead of straight trajectories, resulting in position errors up to 3 cm. The antenna array of the interrogation unit was oriented vertically configuring its aperture over the height of the room. Thus, the ULA was used to define the z-axis, using the floor as origin, as it can be observed in Fig. 3. Then, the synthetic aperture generated by the mobile robot defined the x-axis, where the origin $x_0 = 0$ corresponded to the starting position. Finally, the y-dimension was defined perpendicular to the previously mentioned axes, covering the depth of the room. The antenna positions along the driven trajectory based on the defined coordinate system were then used for the reconstruction algorithm.

V. MEASUREMENT RESULTS

To validate the proposed concept, four SAW tags were located at different positions, and they were simultaneously evaluated with a mobile multi-channel interrogation unit. In this section, the transformation of SAW RFID tag signals is first described, and the interference effects between the multiple signals are analyzed. Based on the superimposed spectrum of the received SAW tag signals, the spatial probability
density function of each signal response is calculated, and the association with their source tags based on their root mean square error (RMSE) to their actual position is assessed. The performance of the experimental results is evaluated in terms of localization accuracy and correct reflector association.

A. SAW TAG SIGNAL PROCESSING
The measured signals from the tags can be considered a sum of complex waveforms, as described in (5), where each reflected signal is demodulated by the interrogation unit as an impulse response with a given pulse position and phase, both defined by the free space and the acoustic wave propagation. To analyze the time-domain pulse coded responses, a chirp-Z transform of the raw data was performed within the delay region of interest of the coding scheme, which was between 1 and 3 μs. This processing step was performed over sequential measurements along a defined synthetic aperture of about 3 m length.

The identification patterns of multiple SAW tag signals with a common pulse-coded scheme arise on top of each other based on the mathematical model presented in Section III, resulting in signal collision, since a superposition of signals takes place due to the limited amount of possible reflector positions. Furthermore, because of the interaction between SAW tags, the effects of constructive and destructive reflector interferences are especially visible when comparing measurements at different physical positions, as shown in Fig. 4. A fluctuating signal is therefore expected along the synthetic aperture in contrast to single tag evaluation, as presented in [20].

In most cases, due to the resolution limit, interrogation units are not able to separate overlapping responses over the delay based exclusively on the free space propagation difference resulting from the individual interrogation element to tag separations since it only adds up a relative small contribution to the RTD due to the faster propagation speed of the electromagnetic waves in relation to the acoustic waves.

In real scenarios, however, the more the tags within the reading range, the higher the probability of overlapping coded pulses. Therefore, in large volume applications, an increasing interaction between tags is expected, with eventual signal loss at particular apertures due to destructive interferences.

B. SPATIAL REFLECTOR SIGNAL RECONSTRUCTION
The measured reflector responses were detected during the interrogation process without assuming the tag encoding was known, as would be done in practice. The signal characteristics of the detected impulse responses were then extracted and correlated with the computed hypothesis using (11) over the interrogation ULA. The absolute phases are not considered, but the relative phase variation depending on the measurement position, in order to reconstruct a reflection point, that is, to resolve it spatially. Since the relative phase differences are the same over the entire width of the selected echoes, it is not required to estimate the exact delays. Therefore, the range migration and the selected size of the apertures do not prevent the algorithm from working. A spatial probability density function was generated containing the estimated location of each response over a 3D map corresponding to the simulated geometrical positions of the room. For reflector responses overlapping at the same RTD position, a multimodal distribution is expected, with a number of modes corresponding to the number of source tags.

In the upper plot of Fig. 5, the interrogation spectrum corresponding to four superimposed SAW tags located at neighboring plastic boxes at the same height on a pallet measured from an arbitrary aperture position is depicted. As it can be observed, the start bit of the coding scheme, which is coded at the same distance from the IDT for all the measured tags, cannot be separated based on the pulse position, since the delay difference between impulse responses is smaller than the resolution limit for unambiguous processing.

Nevertheless, analyzing the corresponding spatial probability density function, as shown in the second plot, multiple correlation maxima can be identified over the hypothesis simulated, which indicates the presence of multiple reflectors superposed on top of each other, where each mode is originated from a different tag source. The highest match between the measured response and the simulated hypothesis over the respective Cartesian dimensions is depicted with a local maxima on the correlation distribution. These appear as distinct peaks (local maxima) in the spatial probability density function generated by the discrete correlation distribution. The actual location of the SAW tags is depicted on the intersection between the dashed lines as ground truth reference.

This process is successively performed for two additional coding reflectors, as shown in the lower plots of the figure. The spatial PDF map of the third detected impulse response, which corresponds to a a unique coding reflector belonging to the SAW tag located at the third plastic box, is unambiguously estimated with a single global maximum over the different dimensions. Likewise, the last plot shows a spatial PDF with two modes, corresponding to an overlapping coding symbol.
FIGURE 5. Final evaluation of multiple SAW tag signal responses that have been simultaneously measured. In the top subfigure, the signal patterns in time-domain are superimposed on top of each other, leading to coincident response signals corresponding to one or more reflector contributions, which cannot be associated with their source tags. On the lower subfigures the spatial PDF of different reflector responses is represented within the range of interest where the tags are located. The reference positions correspond to the intersection of the black dashed lines.

belonging to two different tags placed at the first and third plastic boxes.

Shifts corresponding to the localization error can be observed between the maximum of the spatial PDFs, that is, the estimated locations of the reflectors, and the actual ground truth positions of the tags, corresponding to the center of the black circles at the intersection of the dashed lines. To evaluate this error, the localization accuracy has been estimated computing the RMSE based on the Euclidean distance between the estimated reflector \( p \) position from its corresponding tag \( k \), denoted as \( \hat{r}_{k,p} \) and the actual tag position \( r_k \):

\[
RMSE_{k,p} = \sqrt{\left\| \hat{r}_{k,p} - r_k \right\|^2}.
\]

(13)

In Fig. 6, the RMSE corresponding to each reflector in relation to its source tag is indicated with a scaled color matrix, where the rows indicate the reflectors grouped by their respective tags in increasing order, while each column is associated with an actual tag position.

The location of the reflectors is systematically estimated with a minimum RMSE in relation to their corresponding source tag positions, as it can be observed on the lower values in the diagonal cells. This demonstrates a robust feasibility of the code reconstruction. In total, \( P = 24 \) individual reflector responses corresponding to \( N = 4 \) different SAW tags were estimated. Based on these results, a spatial clustering was implemented with a minimum Euclidean distance threshold of 10 cm. Then, based on these geometrical conditions, the reflector responses can be associated with the SAW tags placed on their respective plastic boxes of the pallet based on their estimated location.

Therefore, even identical SAW tags containing the same acoustic delay coded signals can be separated using the proposed technique. With the estimation of the position of each tag reflector, the free space contribution on the pulse-coded positions can be compensated using the estimated separation between interrogation element and tag, which, in addition to calibration reflectors, introduces an additional robustness for the decoding process. In addition, missing code information can be recovered using error correction techniques.

FIGURE 6. Reflector association matrix summarizing the algorithm localization results. The matrix cells denote the localization RMSE in gray scale of each reflector response against the reference tag positions.

FIGURE 7. Localization results depicted with the estimated positions of the individual SAW RFID reflectors projected in a 3D Cartesian map. The estimated reflector positions are represented with black circles, while the reference positions of the tags are marked with gray crosses and the synthetic aperture resulting from the positions driven by the interrogation unit elements are depicted with black crosses.

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In Fig. 7, the localization results for each impulse response in relation to the room size and the interrogation range in three dimensions are depicted. The estimated reflector positions are represented with black circles, together with the actual positions of the SAW tags, represented with gray crosses, and the actual transceiver positions driven by the interrogation system, marked with black crosses.

Slight position deviations can be observed, which are acceptable in relation to the room size and reading range. The performance of the system fulfills the requirement for correct reflector to tag association, while showing an accurate position estimation of the SAW tag for asset management applications in even harsh multipath environments.

Once the reflectors have been clustered based on their estimated position, the individual spatial probability density functions corresponding to each detected signal are integrated to obtain the tag location estimate. The 3D localization results are presented in Table 1.

The signal interaction between the simultaneously measured SAW tags causes constructive and destructive interferences over the synthetic aperture, which deteriorates the phase measurements used for the holographic reconstruction algorithm. Therefore, the experimental situation introduces an error that reduces the localization performance in relation to previous work [20], [21]. Nevertheless, the system is capable of localizing the correct tags on a pallet with an appropriate accuracy for the application in relation to the reading range and the box dimensions.

Besides, the proposed SDMA approach can also be applied on different tag distributions. Large angles of incidence deteriorate the distance resolution between reader and tag while having a minimal impact on the angular resolution [22]. Nevertheless, in the presented approach, the distance resolution is not mainly obtained from the aperture over the antenna array, but from the synthetic aperture.

### VI. CONCLUSION

Multiple tag access and 3D SAW reflector response localization in centimeter range have been achieved in this work under a harsh multipath environment. Based on spatial clustering, the detected impulse responses have been correctly associated with their SAW tags based on the clustering of the reflector delays assigned to the corresponding spatial locations where the tagged objects are found. In comparison with other anticollision techniques found in the literature, the multiple tag access concept proposed in this work can be implemented on most commercial SAW tag coding schemes. On top of that, a gain on robustness against interferences from a multiple tag indoor scenario was achieved and all the actually present signal reflections were identified, since the spatial diversity concept has allowed compensation of interference effects between reflectors and reduction of multipath effects through the coherent integration of signals along the synthetic aperture, which, in addition, enhances the SNR of the signals.

Based on the measurement results, this technology can be used for high-volume asset management using multiple access SAW RFID technology, enabling identification and localization of assets also under harsh conditions, where SAW technology offers good performance. Furthermore, the localization and reflector separation performance of the system can be improved along the different dimensions using alternative antenna array configurations, as well as a modified synthetic aperture trajectory. Besides, the shown methodology can be applied in combination with other approaches from information theory and multiuser communication to develop coding schemes with superior performance.

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