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The Applicability of RFID for Indoor Localization

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1. Introduction

Although RFID has a relatively long history of more than 50 years in the field of wireless communications, only the last decade it has received a considerable attention for becoming a useful general purpose technology. Actually, RFID was initially developed as an automatic identification system consisting of two basic component types, a reader and a tag (Want, 2006). The reader is able to read the IDs of tags in its vicinity by running a simple link-layer protocol over the wireless channel. RFID tags can be either active or passive depending on whether they are powered by battery or not, respectively. Passive tags are prevalent in supply chain management as they do not need a battery to operate. This makes their lifetime large and cost negligible. The low cost of passive tags, the non-LOS requirement, the simultaneous reading of multiple tags and the reduced sensitivity regarding user orientation motivated the academia and industry for exploring its potentials in more intelligent applications Baudin & Rao (2005).

This chapter studies whether an RFID deployment can be applied for the purpose of indoor localization. It is widely accepted that location awareness is an indispensable component of the future ubiquitous and mobile networks and therefore efficient location systems are mandatory for the success of the upcoming era of pervasive computing. However, while determining the location of objects in outdoor environments has been extensively studied and addressed with technologies such as the Global Positioning System (GPS) (Wellenhoff et al., 1997), the localization problem for indoor radio propagation environments is recognized to be very challenging, mainly due to the presence of severe multi-path and shadow fading. The key properties of RFID motivated the research over RFID-based positioning schemes. Correlating tag IDs with their location coordinates is the principle concept for their realization.

Though RFID offers promising benefits for accurate and fast tracking, there are some technology challenges that need to be addressed and overcome in order to fully exploit its potential. Indeed, the main shortcoming of RFID is considered the interference problem among its components, mainly due to the limited capabilities of the passive tags and the inability of communication between readers (GP & SW, 2008). There are three main types of RFID interference. The first one is due to the responses of multiple tags to a single reader's query, the second is related to the queries of multiple readers to a single tag and finally, the third is due to the low signal power of weak tag responses compared to the stronger neighbor readers' transmissions. The first type affects the time response of the system, whereas the other two reduce the positioning accuracy. In addition, interference from non-conductive materials such as metal or glass imposes one more concern regarding the appropriateness of RFID for widespread deployment.

In this chapter, deploying cheap RFID passive tags within an indoor environment in order to determine the location of users with reader-enabled mobile terminals is proposed. The rationale behind selecting such configuration is mainly due to the low cost of passive tags, making their massive deployment a cost-effective solution. Moreover, next generation mobile terminals are anticipated to support RFID reading capabilities for accessing innovative tag-identifiable services through the RFID network. Three popular positioning algorithms are compared. The reason of their selection is because they can be all easily implemented on either the mobile or a central engine but they differ in their processing requirements. This chapter also studies the impact of several system design parameters such as the positioning algorithm, the tag deployment and the read range, on the accuracy and time efficiency objectives. Finally, mechanisms for dealing with these problems are also discussed.

The rest of this chapter is organized as follows: section 2 provides essential background for indoor localization and popular RFID positioning systems. In section 3 we explain the main shortcomings of RFID regarding localization which was our main motivation for conducting this study. In section 4 the conceptual framework of a RFID-based positioning system is described and section 5 provides simulation-based analysis results. Finally, in section 6 we give our main conclusions.

2. Background and related work

This section provides an overview of the indoor localization problem and a literature review in RFID indoor positioning systems.

2.1 Indoor localization

The localization problem is defined as the process of determining the current position of a user or an object within a specific region, indoor or outdoor. Position can be expressed in several ways depending on the application requirements or the positioning system specifications.

Localization using radio signals has attracted considerable attention in the fields of telecommunication and navigation. The most well known positioning system is the Global Positioning System (GPS) (Wellenhoff et al., 1997), which is satellite-based and very successful for tracking users in outdoor environments. However, the inability of satellite signals to penetrate buildings causes the complete failure of GPS in indoor environments. The indoor radio propagation channel is characterized as site specific, exhibiting severe multi-path effects and low probability of line-of-sight (LOS) signal propagation between the transmitter and the receiver (Pahlavan & Levesque, 2005), making accurate indoor positioning very challenging. For indoor location sensing a number of wireless technologies have been proposed, such as infrared (Want et al., 1992), ultrasound (Priyantha et al., 2000), WiFi (Bahl & Padmanabhan, 2000), (Youssef & Agrawala, 2005), (King et al., 2006), (Papapostolou & Chaouchi, 2009a), (Ubisense, n.d.), UltraWideBand (UWB) (Ingram et al., 2004), and more recently RFID (Hightower et al., 2000), LANDMARC, (Ni et al., 2004), (Wang et al., 2007), (Papapostolou & Chaouchi, 2009b).

Localization techniques, in general, utilize metrics of the Received Radio Signals (RRSs). The most traditional received signal metrics are based on angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA) measurements or received signal strength (RSS) measurements from several Reference Points (RPs). The reported signal metrics are then processed by the positioning algorithm for estimating the unknown location of the receiver, which is finally utilized by the application. The accuracy of the signal metrics and the complexity of the positioning algorithm define the accuracy of the estimated location.

Depending on how the signal metrics are utilized by the positioning algorithm, we can identify three major families of localization techniques (Hightower & Borriello, 2001), namely *triangulation*, *scene analysis* and *proximity*.

2.1.1 Triangulation

Triangulation methods are based on the geometric properties of a triangle to estimate the receiver's location. Depending on the type of radio signal measurements, triangulation can be further subdivided into *multi-lateration* and *angulation* method. In *multi-lateration* techniques, TOA, TDOA or RSS measurements from multiple RPs are converted to distance estimations with the help of a radio propagation model. Examples of such positioning systems include GPS (Wellenhoff et al., 1997), the Cricket Location System (Priyantha et al., 2000), and the SpotON Ad Hoc Location (Hightower et al., 2000). However, models for indoor localization applications must account for the effects of harsh indoor wireless channel behavior on the characteristics of the metrics at the receiving side, characteristics that affect indoor localization applications in ways that are very different from how they affect indoor telecommunication applications. In *angulation* techniques, AOA measurements with the help of specific antenna designs or hardware equipment are used for inferring the receiver's position. TheUbisense (Ubisense, n.d.) is an example of AOA-based location sensing system. The increased complexity and the hardware requirement are the main hindrances for the wide success of such systems.

2.1.2 Scene analysis/fingerprinting

Scene analysis or *fingerprinting* methods require an offline phase for learning the RRS behavior within a specific area under study. This signal information is then stored in a database called *Radio Map*. During the real-time localization phase, the receiver's unknown location is inferred based on the similarity between the Radio Map entries and the real-time RSS measurements. RADAR (Bahl & Padmanabhan, 2000), HORUS (Youssef & Agrawala, 2005), COMPASS (King et al., 2006) and WIFE (Papapostolou & Chaouchi, 2009b) follow this approach. The main shortcoming of scene analysis methods is that they are susceptible to uncontrollable and frequent environmental changes which may cause inconsistency of the signal behavior between the training phase and the time of the actual location determination phase.

2.1.3 Proximity

Finally, *proximity* methods are based on the detection of objects with known location. This can be done with the aid of sensors such as in Touch MOUSE (Hinckley & Sinclair, 1999), or based on topology and connectivity information such as in the Active Badge Location System (Want et al., 1992), or finally with the aid of an automatic identification system, such as credit card point of cell terminals. Such techniques are simple but usually suffer from limited accuracy.

2.2 RFID positioning systems

RFID positioning systems can be broadly divided into two classes: *tag* and *reader localization*, depending on the RFID component type of the target.

In *tag localization* schemes, readers and possibly tags are deployed as reference points within the area of interest and a positioning technique is applied for estimating the location of a tag. SpotON (Hightower et al., 2000) uses RSS measurements to estimate the distance between a target tag and at least three readers and then applies trilateration on the estimated

System	Target	Deployment	Approach	Accuracy
Hightower et al. (2000)	Tag	Readers	RSS trilateration	3 m
Ni et al. (2004)	Tag	Readers & Tags	RSS Scene Analysis	1 - 2 m
Wang et al. (2007)	Tag	Readers & Tags	RSS proximity and optimization	0.3 - 3 ft
Stelzer et al. (2004)	Tag	Readers & Tags	TDoA weighted mean squares	-
Bekkali et al. (2007)	Tag	Readers & Tags	RSS mean squares and Kalman filtering	0.5 - 5 m
Lee & Lee (2006)	Reader	Tags (dense)	RSS Proximity	0.026 m
Han et al. (2007)	Reader	Tags (dense)	Training and RSS Proximity	0.016 m
Yamano et al. (2004)	Reader	Tags	RSS Scene Analysis	80%
Xu & Gang (2006)	Reader	Tags	Proximity and Bayesian Inference	1.5 m
Wang et al. (2007)	Reader	Tags	RSS proximity and optimization	0.2 - 0.5 ft

Table 1. RFID Localization systems.

distances. LANDMARC (Ni et al., 2004) follows a scene analysis approach by using readers with different power levels and reference tags placed at fixed, known locations as landmarks. Readers vary their read range to perform RSS measurements for all reference tags and for the target tag. The k nearest reference tags are then selected and their positions are averaged to estimate the location of the target tag. Wang et al. (Wang et al., 2007) propose a 3-D positioning scheme which relies on a deployment of readers with different power levels on the floor and the ceiling of an indoor space and uses the Simplex optimization algorithm for estimating the location of multiple tags. LPM (Stelzer et al., 2004) uses reference tags to synchronize the readers. Then, TDoA principles and ToA measurements relative to the reference tags and the target tag are used to estimate the location of the target tag. In (Bekkali et al., 2007) RSS measurements from reference tags are collected to build a probabilistic radio map of the area and then, the Kalman filtering technique is iteratively applied to estimate the target’s location. If the target is a RFID reader, usually passive or active tags with known coordinates are deployed as reference points and their IDs are associated with their location information. In (Lee & Lee, 2006) passive tags are arranged on the floor at known locations in square pattern. The reader acquires all readable tag locations and estimates its location and orientation by using weighted average method and Hough transform, respectively. Han et al. (Han et al., 2007) arrange tags in triangular pattern so that the distance in x-direction is reduced. They show that the maximum estimation error is reduced about 18% from the error in the square pattern. Yanano et al. (Yamano et al., 2004) utilize the received signal strength to determine the reader position by using machine learning technique. In the training phase, the reader acquires the RSS from every tag in various locations in order to build a Support Vector Machine (SVM). Since it is not possible to obtain the signal intensity from every location, they also propose a method to synthesize the RSS data from real RSS data acquired in the training phase. When the reader enters the area, it will pass the received signal intensity vector to the SVM to determine its position. A Bayesian approach is also proposed to predict the position of a moving object (Xu & Gang, 2006). Having the posterior movement probability and the detected tags’ locations, the reader location is determined by maximizing the posterior probability. Then, the reader position is calculated by averaging the inferred position from all tags. However, the accuracy of the algorithm depends on the movement probability model. Finally, (Wang et al., 2007) proposes also a reader localization scheme by employing the Simplex optimization method. Table 1 summarizes the main characteristics of the above systems.

Apparently, selecting a best scheme is not trivial since it depends on several factors such as deployment cost, processing requirements, time and power constraints, scalability issues

etc. The second type of positioning schemes attracted our attention because they are easier to be implemented since low cost passive tags can be deployed in a large extent in most indoor environments. Additionally, it is anticipated that future mobile terminals will have a reader extension capability for gaining access at a wide range of innovative applications and services supported by RFID systems. However, there is lack in the literature of a research study regarding the impact of the interference problem, persisting in RFID, on the localization performance. To that end, we have selected three positioning algorithms differing in their complexity level in order to investigate their behavior when multiple reader-enabled mobile nodes need to be localized simultaneously. We believe that examining this parameter is crucial for verifying the efficiency of employing RFID in general location sensing applications.

3. RFID shortcomings

The communication link between the main RFID components is half duplex, reader to tag and then tag to reader. In the forward link, the reader's transmitting antenna (transmitter) sends a modulated carrier to tags to power them up. In the return link, each tag receives the carrier for power supply and backscatters by changing the reflection coefficients of the antenna. In such a way, its ID is sent to the reader's receiving antenna (receiver). The path loss of this two way link may be expressed as:

$$PL(d) = PL_o + 10N \log \left(\frac{d}{d_o} \right) + X_\sigma, \quad (1)$$

where d the distance between the reader and a tag, PL_o the path loss at reference distance d_o given by $PL_o = G_t G_r (g_t \Gamma g_r) \left(\frac{\lambda}{4\pi d_o} \right)^4$ and G_t , g_t , and G_r , g_r are the gains of the reader and tag transmit and receive antennas, respectively. Γ is a reflection coefficient of the tag and λ the wavelength. $N = 2n$, where n the path loss component of the one way link. The path loss model defines the received power $RSS(d)$ at the receiver given the transmit power P_t of the transmitter, i.e.:

$$RSS(d) = P_t - PL(d). \quad (2)$$

In the absence of interference, the maximum read range a reader receiver can decode the backscattered signal is such that:

$$R_{max} = \arg \max_{d \geq 0} RSS(d) \geq TH, \quad (3)$$

where TH represents a threshold value for successful decoding.

Even though RFID technology has promising key characteristics for location sensing, it has also some limitations which become more intense in the case of simultaneous tracking in a multi-user environment and thus should be taken into account before employing an RFID system for localization.

Since RFID technology uses electromagnetic waves for information exchange between tags and readers, how radio waves behave under various conditions in the RFID interrogation zone (IZ) affects the performance of the RFID system. Radio waves propagate from their source and reach the receiver. During their travel, they pass through different materials, encounter interference from their own reflection and from other signals, and may be absorbed or blocked by various objects in their path. The material of the object to which the tag is attached may change the property of the tag, even to the point it is not detected by its reader.

However, the most harmful type of interference is the one among its components which is known as the RFID collision problem. Three are its main types: tag collision, multiple reader-to-tag collision and reader-to-reader collision.

3.1 Multiple tags-to-reader interference

When multiple tags are simultaneously energized by the same reader, they reflect simultaneously their respective signals back to the reader. Due to a mixture of scattered waves, the reader cannot differentiate individual IDs from the tags. This type of interference is known as multiple tags-to-reader interference or tag identification problem.

3.1.1 Anti-collision algorithms

For resolving multiple tag responses an anti-collision mechanism is essential. Reviewing the literature, several anti-collision protocols have been proposed, such as time-division multiple or binary tree-based schemes (GP & SW, 2008). For instance, the EPCglobal (EPCglobal, n.d.), an organization that recognized the potential of RFID early, proposed bit-based Binary Tree algorithm (deterministic) and Aloha-based algorithm (probabilistic). The International Standards Organization (ISO) as part of the ISO 18000 family proposed the Adaptive Protocol which is similar to the Aloha-based algorithm proposed by EPCglobal, and binary tree search algorithm. These protocols mainly differ in the number of tags that can be read per second, their power and processing requirements.

In this work, we selected the Pure and Slotted Aloha schemes (Klair et al., 2009) as basis for our analysis. Let \mathcal{D}_u the set of tags simultaneously energized by the reader r_u . When reading starts, each tag transmits its ID irrespectively of the rest $|\mathcal{D}_u| - 1$ tags. The communications from a tag to the reader is modeled as a Poisson process (Schwartz, 1986). Each tag responds on average λ times per second. The model requires independence among tag transmissions, which is supported by the lack of tag-to-tag communication capabilities. Since each tag's transmission is Poisson distributed, there is a mean delay of $1/\lambda$ between consecutive transmissions. This is referred to as the arrival delay (Schwartz, 1986). Thus, on average each tag takes $\frac{1}{|\mathcal{D}_u|\lambda}$ time to transmit its ID for the first time. This is referred as arrival delay (Schwartz, 1986). During collisions, colliding tags retransmits after a random time. In Aloha-based schemes, the retransmission time is divided into K time slots of equal duration s and each tag transmits its ID at random during one of the next time slots with probability $1/K$. This means tags will retransmit within a period of $K \times s$ after experiencing a collision. On average, a tag will retransmit after a duration of $\frac{K+1}{2} \times s = a$ slots. The number of collisions before a tag successfully responds is $e^{xG_A} - 1$, where e^{xG_A} denotes the average number of retransmission attempts made before a successful identification, where $G_A = |\mathcal{D}_u|\lambda s$ is the offered load and $x = 1$ for Pure Aloha (PA) and $x = 2$ for Slotted Aloha (SA). Since each collision is followed by a retransmission, the average delay before a successful response is $(e^{xG_A} - 1)a$, followed by a single successful transmission of duration s . In total, the average delay a tag takes to transmit its ID successfully is $t_{TR} = (e^{xG_A} - 1)as + s + \frac{1}{|\mathcal{D}_u|\lambda}$. For non-saturated case, i.e. tags to be detected are less than the maximum number of tags that can be read per inventory round, the total time needed for reading successfully $|\mathcal{D}_u|$ tags follows the linear model

$$T_{TR} = |\mathcal{D}_u| \times t_{TR} = |\mathcal{D}_u| \times \left\{ s \left[1 + (e^{xG_A} - 1)a \right] + \frac{1}{|\mathcal{D}_u|\lambda} \right\}. \quad (4)$$

3.2 Multiple readers-to-tag interference

Multiple readers-to-tag interference occurs when a tag is located at the intersection of two or more readers' interrogation range and the readers attempt to communicate with this tag simultaneously. Let R_i and R_j denote the read ranges of readers r_i and r_j and d_{ij} their distance. Apparently, if

$$R_i + R_j > d_{ij} \quad (5)$$

and r_i and r_j communicate at the same time, they will collide and the tags in the common area will not be detected.

Figure 1(a) depicts two readers r_1 and r_2 which transmit simultaneously query messages to a tag t_1 situated within their overlapping region. t_1 might not be able to read the query messages from neither r_1 nor r_2 due to interference.

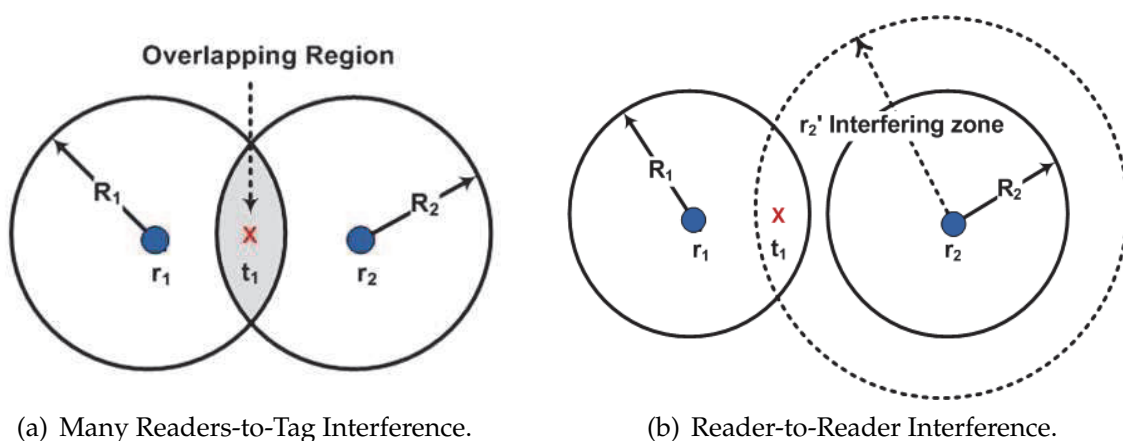


Fig. 1. Two types of interference in RFID.

3.2.1 Reader collision probability

The probability P_{ij}^C of such collision type between readers r_i and r_j , if equation (5) is satisfied, depends on the probabilities r_i and r_j are simultaneously trying to communicate with their common tag. For characterizing the probability of simultaneous reader communication, we assume that each reader is in a scanning mode with probability p^{scan} . Thus, P_{ij}^C depends on the probabilities r_i and r_j are in a scanning mode, p_i^{scan} and p_j^{scan} , respectively, i.e.

$$P_{ij}^C = p_i^{scan} \times p_j^{scan}. \quad (6)$$

A mechanism coordinating reader transmissions as the one proposed in (Papapostolou & Chaouchi, 2009a) can compensate this type of interference.

3.3 Reader-to-reader interference

Reader-to-reader interference is induced when a signal from one reader reaches other readers. This can happen even if there is no intersection among reader interrogation ranges ($R_i + R_j < d_{ij}$) but because a neighbor reader's strong signal interferes with the weak reflected signal from a tag. Figure 1(b) demonstrates an example of collision from reader r_2 to reader r_1 when the latter tries to retrieve data from tag t_1 . Generally, signal strength of a reader is superior to that of a tag and therefore if the frequency channel occupied by r_2 is the same as that between t_1 and r_1 , r_1 is no longer able to listen to t_1 's response.

3.3.1 Read range reduction

Reader-to-reader interference affects the read range parameter. In equation (3) this factor had been neglected. However, when interfering readers exist, the actual interrogation range of the desired reader decreases to a circular region with radius R_{max}^I , which can be represented by

$$R_{max}^I = \arg \max_{d \in [0, R_{max}]} SIR(d) \geq TH, \quad (7)$$

where

$$SIR(d) = \frac{P_s(d)}{\sum_i I_i} \quad (8)$$

and I_i the interference from reader r_i .

The Class 1 Gen 2 Ultra High Frequency (UHF) standard ratified by EPCGlobal (EPCglobal, n.d.), separates the readers' from tags' transmissions spectrally such that tags collide only with tags and readers collide only with readers.

4. RFID Positioning system framework

From architectural point of view, a location determination scheme can be either user-based or network-based. In the first case, each user is responsible for collecting and processing information necessary for determining his location, whereas, in the second case, a dedicated server is responsible for gathering all required data and finally providing the location estimates for all users. Processing capabilities, privacy and scalability issues, link quality are usually the main factors for selecting the appropriate approach. Since a RFID system includes tags, readers and servers, we propose a hybrid architecture as a compromise between them, i.e. both user and a dedicated location server participate in the location decision process.

Figure 2 depicts the proposed architecture. The reader embedded at each user device queries for reference tags within its coverage in order to retrieve their IDs. Then, the list of the retrieved tag IDs with the corresponding RSS levels is forwarded to the *Location Server* within a TAGLIST message. Based on the received TAGLIST messages and a repository which correlates the IDs of the *reference* tag with their location coordinates, the *Location Server* estimates the location for all users by employing a RFID-based positioning (see subsection 4.1) algorithm and finally returns the estimated locations back to the corresponding users in LOCATIONESTIMATE messages.

The communication between the reader and the tags is done through the RF interface of the reader, whereas the communication between the reader and the server is possible through the communication interface of the reader, such as IEEE 802.11. Alternatively, assuming multi-mode devices, the TAGLIST and location estimation messages can be exchanged by the wireless interface of the user device.

It is worthy mentioning that the proposed architecture may not be always the optimal choice. For example, if the wireless medium between users and the *Location Server* is not robust enough for exchanging messages successfully, a user-based approach would be more efficient. In this case, when a new user enters the indoor area it can receive information regarding the tag deployment automatically or after having subscribed to a relevant service. Then, by following a positioning algorithm, it can estimate its own location. However, in such approach, greater attention should be given regarding the complexity of the positioning algorithm since mobile terminals have limited resources compared to servers.

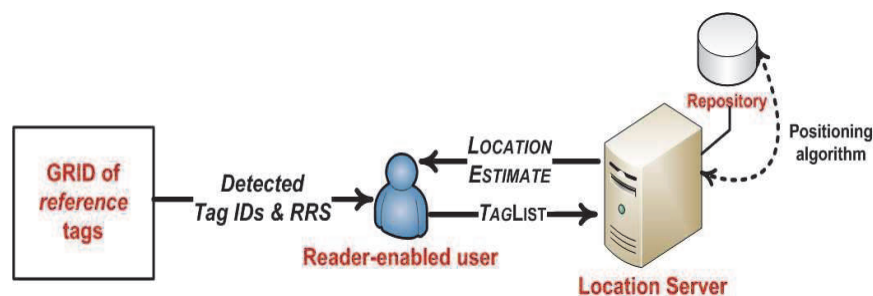


Fig. 2. Proposed RFID-based Positioning Architecture.

4.1 Positioning algorithms

A positioning algorithm defines the method of processing the available information in order to estimate the target's location. The main metrics for evaluating its performance are its accuracy, memory requirements and complexity. In this paper, we study three positioning algorithms which can be easily implemented in the sense that they do not require any special hardware, but differ in their complexity and memory requirements.

Let \mathcal{D}_u denote the set of *reference* tags successfully detected from a user's reader r_u and \mathbf{SS}_u a vector of the corresponding RSS measurements such that the entry RSS_t is the RSS from the tag $t \in \mathcal{D}_u$ to r_u .

4.1.1 Simple Average (SA)

This algorithm is based on the assumption that the reader radiation pattern forms a perfect circle. Thus, the user's location is estimated as the simple average of the coordinates (x_t, y_t) of all tags $t \in \mathcal{D}_u$, i.e.:

$$(\hat{x}_u, \hat{y}_u) = \left(\frac{\sum_{t \in \mathcal{D}_u} x_t}{|\mathcal{D}_u|}, \frac{\sum_{t \in \mathcal{D}_u} y_t}{|\mathcal{D}_u|} \right) \quad (9)$$

This scheme has the minimum memory requirements since only the ID information from the detected *reference* tags is used for estimating the unknown location. Regarding its processing requirements, it involves $2 \times |\mathcal{D}_u|$ additions of the coordinates of the detected tags and 2 divisions. Therefore, it has linear complexity $O(|\mathcal{D}_u|)$.

4.1.2 Weighted Average (WA)

Since some of the detected tags may be closer than others, biasing the simple averaging method is proposed as an alternative approach. This can be achieved by assigning a weight w_t to the coordinates of each tag $t \in \mathcal{D}_u$. These weights are based on their RSS from the reader. Thus, (9) becomes:

$$(\hat{x}_u, \hat{y}_u) = \left(\frac{\sum_{t \in \mathcal{D}_u} w_t \cdot x_t}{\sum_{t \in \mathcal{D}_u} w_t}, \frac{\sum_{t \in \mathcal{D}_u} w_t \cdot y_t}{\sum_{t \in \mathcal{D}_u} w_t} \right) \quad (10)$$

where $w_t = 1/|RSS_t|$ and RSS_t the measured RSS value from tag t .

This scheme requires more memory than the SA, since RSS information is used in addition to tags' IDs for estimating the unknown location. Regarding its processing requirements, it involves $4 \times |\mathcal{D}_u|$ addition, $2 \times |\mathcal{D}_u|$ multiplication and 2 division operations. Thus, its complexity remains linear, i.e. $O(|\mathcal{D}_u|)$.

4.1.3 Multi-Lateration (ML)

Finally, we investigate a multi-lateration based approach which tries to take into account the imperfection of the readers' radiation pattern. The distances from all detected tags \mathcal{D}_u are first estimated and then (x_u, y_u) can be obtained by solving the following system of $|\mathcal{D}_u|$ equations:

$$\begin{aligned} (x_1 - x_u)^2 + (y_1 - y_u)^2 &= \hat{d}_1^2 \\ &\vdots \\ (x_{|\mathcal{D}_u|} - x_u)^2 + (y_{|\mathcal{D}_u|} - y_u)^2 &= \hat{d}_{|\mathcal{D}_u|}^2 \end{aligned} \quad (11)$$

The above system of equations is not linear. According to (Caffery, n.d.) it can be linearized by subtracting the last equation from the first $|\mathcal{D}_u| - 1$ equations. The resulting system of linear equations is given then given by the following matrix form:

$$\mathbf{A}[x_u, y_u]^T = \mathbf{b}, \quad (12)$$

where

$$\mathbf{A} := \begin{pmatrix} 2(x_1 - x_u) & 2(y_1 - y_u) \\ \vdots & \vdots \\ 2(x_{|\mathcal{D}_u|} - x_u) & 2(y_{|\mathcal{D}_u|} - y_u) \end{pmatrix}, \quad (13)$$

$$\mathbf{b} := \begin{pmatrix} x_1^2 - x_{|\mathcal{D}_u|}^2 + y_1^2 - y_{|\mathcal{D}_u|}^2 + \hat{d}_1^2 - \hat{d}_{|\mathcal{D}_u|}^2 \\ \vdots \\ x_{|\mathcal{D}_u|-1}^2 - x_{|\mathcal{D}_u|}^2 + y_{|\mathcal{D}_u|-1}^2 - y_{|\mathcal{D}_u|}^2 + \hat{d}_{|\mathcal{D}_u|-1}^2 - \hat{d}_{|\mathcal{D}_u|}^2 \end{pmatrix}.$$

Since \hat{d}_t are not accurate, the above system of equations can be solved by a standard LS approach (Caffery, n.d.) as:

$$[\hat{x}_u, \hat{y}_u]^T = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b} \quad (14)$$

with the assumption that $\mathbf{A}^T \mathbf{A}$ is nonsingular and $|\mathcal{D}_u| \geq 3$, i.e. at least three tags are detected. This scheme has similar memory requirements with the WA. However, it has polynomial complexity $O(|\mathcal{D}_u|^3)$ and it involves complex matrix operations such as creating an inverse matrix.

5. Performance analysis

In this section we evaluate the performance of our approach through simulations, using Matlab, (Matlab, n.d.), as our simulation tool. As performance metric we use the Mean Location Error (MLE) and Mean Localization Time (MLT). MLE is defined as the Euclidean distance between the actual and the estimated position of a user. The MLT includes the time T_{TR} needed for retrieving successfully all $|\mathcal{D}_u|$ tags' IDs within range, given by eq. (4), the processing time of the positioning algorithm, which depends on its complexity and the time needed for sending successfully the TAG LIST message from the reader (or user terminal) to the server and the time needed for sending successfully the location estimation from the server to the reader (or user terminal).

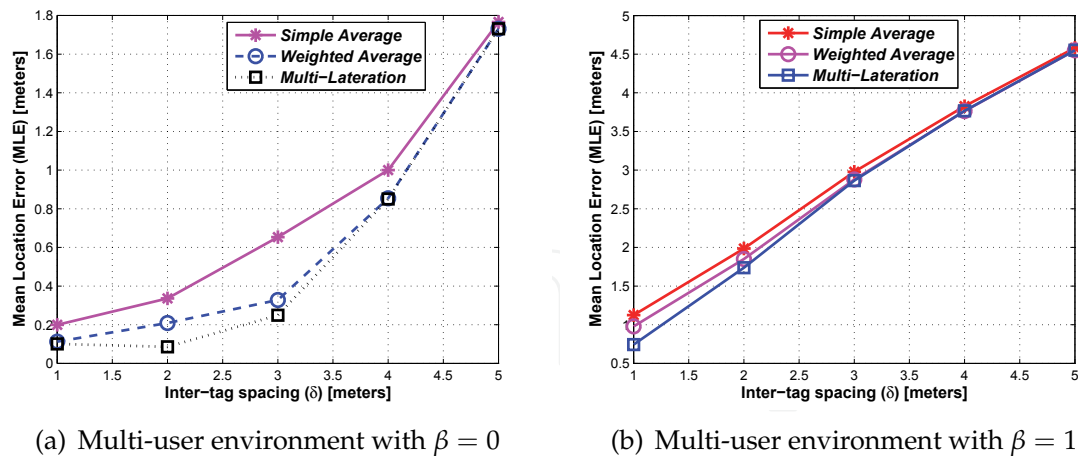


Fig. 3. Impact of tag density (δ)

We provide and interpret results of the simulations we conducted for evaluating the impact of the parameters δ , β , and R_{max} on the system performance. In order to illustrate the performance degradation due to the collision problem and the essentiality of an anti-collision mechanism, we considered two multi-user environmental cases which differ in the level of the collision problem. Assuming that the probability user readers query their tags follows uniform distribution $U(\beta, 1)$, we set $\beta = 0$ for the first case and $\beta = 1$ for the second case. Apparently, for the second environment all users readers scan simultaneously for their tags and thus its performance is anticipated to be worse due to the collision problem among them.

5.1 Localization accuracy

Figures 3(a) and 3(b) illustrate the dependency of the MLE on the tag density, δ , when $\beta = 0$ and $\beta = 1$, respectively, and for the three RFID-based positioning methods described in subsection 4.1, i.e. AVG, W-AVG and ML. For all cases, increasing the inter-tag spacing reduces the accuracy. However, when the collision problem is severe, the achieved accuracy and performance reduction are worse and thus a dense tag deployment is required for providing robustness. Finally, comparing the behavior of the three positioning schemes, we note that there is a benefit from the added complexity but in highly colliding environments the achieved benefit is not significant.

In figures 4(a) and 4(b) the influence of the maximum read range, R_{max} , is depicted when $\delta = 2$. For both scenarios we observe that when $R_{max} = 1$, the MLE is increased and this is because tags are not detected. When $\beta = 0$, $R_{max} = 2$ gives the optimum performance for two main reasons; further than this collisions are more probable but also location information from far-away tags is included. For the second case, the optimum performance is achieved when $R_{max} = 3$ meters because of the collisions which prevents tags from being detected.

5.2 Time response

In Figure 5 we study the time-response performance of the positioning system, focusing on the time needed for retrieving the ID information from detected tags, i.e. T_{TR} . From equation (4) we see that T_{TR} depends on the total number of detected tags $|\mathcal{D}_u|$ and the PA or SA anti-collision algorithm which affects parameter x . $|\mathcal{D}_u|$ depends on the reference tag density δ and the read range R_{max} . Obviously, as δ increases $|\mathcal{D}_u|$ decreases, whereas when R_{max} is higher more tags are detected. The MLT versus the inter-tag spacing δ for both anti-collision

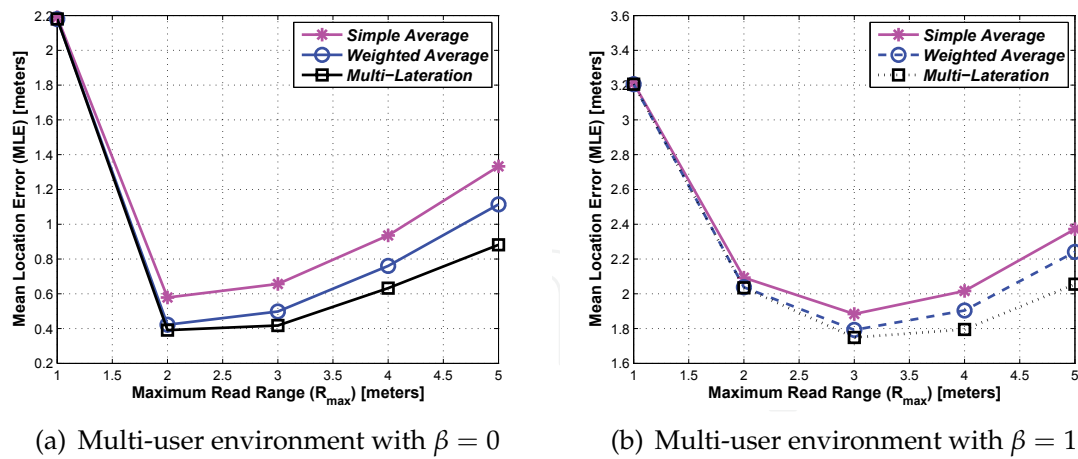


Fig. 4. Impact of maximum read range (R_{max})

algorithms when $R_{max} = 3m$ and $R_{max} = 5m$ is depicted in Figure 5(a) and Figure 5(b), respectively. First of all, we observe that Slotted Aloha has better performance than Pure Aloha, due to the reduction of the vulnerability period $2s$ (Burdet, 2004). In both figures, when the grid deployment is dense, the tag reading time is very high due to the big number of responding tags. Comparing the two cases of R_{max} values, when $R_{max} = 3m$ less tags are within a reader’s interrogation zone and thus, less reading time is required. Finally, recalling Figure, we conclude that there is a trade-off between the accuracy and time response objectives, regarding the optimal value of δ . More tags provide more information for the location determination process but on the other hand more time is required for detecting them.

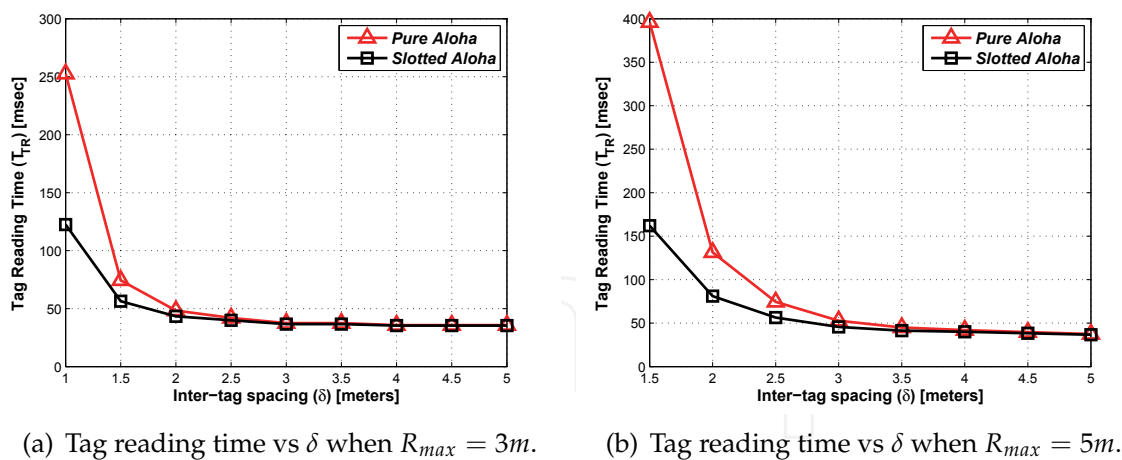


Fig. 5. Impact of system design parameters on Time Response.

Figure 6 depicts the processing time T_{pr} (specified in flops¹) of each positioning algorithm as the inter-tag spacing increases, for $R_{max} = 3m$ and $R_{max} = 5m$ in figures 6(a) and

¹ The execution time of a program depends on the number of floating-point operations (FLOPs) involved. Every computer has a processor speed which can be defined in flops/sec. Knowing the processor speed and how many flops are needed to run a program gives us the computational time required: Time required (sec) = Number of FLOPs/Processor Speed (FLOP/sec) (Canale, n.d.).

6(b), respectively. The main observation is the high processing time of the Multi-Lateration approach for dense tag deployments. The most interesting remarks, however, can be made if Figure is taken into account. The W-AVG approach has the best performance if both objectives are considered. Moreover, for $R_{max} = 5m$ and $\delta = 5m$, the accuracy of the ML technique is high without considerable processing cost. Therefore, more sophisticated techniques can alleviate the need for carefully designed systems.

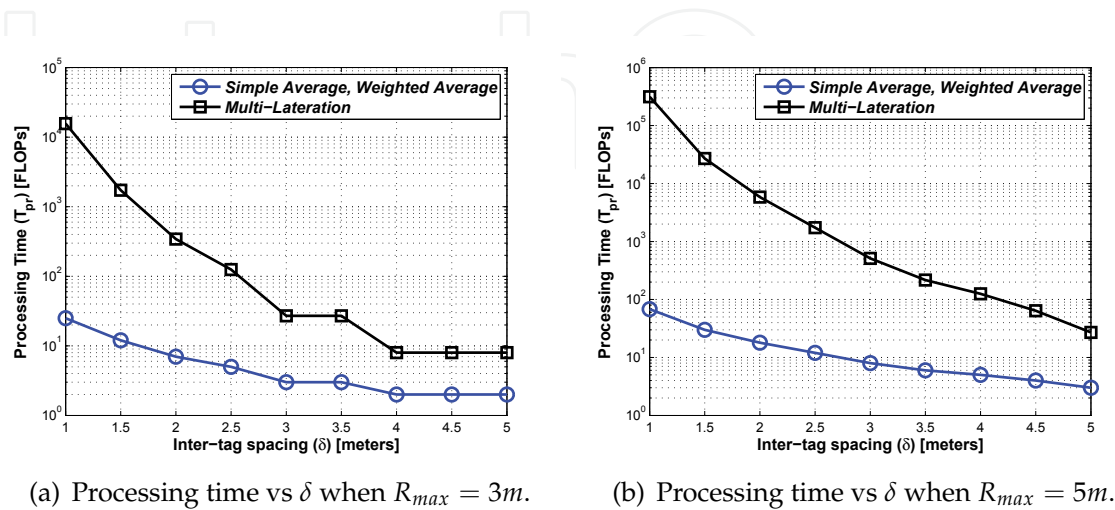


Fig. 6. Impact of positioning algorithm on *Time Response*.

Finally in Table 2 we summarize the main advantages and disadvantages of the system design parameters regarding their accuracy, time response, complexity and behavior under different environmental situations.

6. Conclusion

The growing popularity of the RFID technology and the increasing demand for intelligent location-aware services in indoor spaces motivated exploring its potential for providing accurate and time efficient localization with low deployment cost. However, despite the great benefits RFID can offer, the interference among its components and some materials are its main limiting factors. Therefore the impact of the RFID interference problem on the positioning performance should be extensively studied before the deployment of RFID-assisted location systems.

In this chapter, we explore the applicability of the RFID technology in location sensing and the main design and environmental factors that should be considered before developing an RFID-based localization scheme. We focused on a scenario when the location of multiple reader-enabled terminals needs to be estimated based on the information retrieved from low cost passive tags, which are deployed in an area. We proposed a mathematical model for taking into account all implicating factors which affect the accuracy performance of the system, that is all types of collisions among its components, interference from materials, and temporal environmental changes. Extensive simulations were conducted to evaluate the impact of these parameters. More precisely, when reader collisions is not an issue, a low dense ($\delta \leq 4$ meters) deployment of passive tags can provide an accurate location information with error less than 1 meter. However, in a highly colliding environment, passive tags should be deployed with spacing of 1 meter in order to have similar location error resilience. Interesting remarks can be drawn regarding the communication range of readers.

Design Parameter		Pros	Cons
Reference Tag Deployment	$\delta : [5 \rightarrow 1]m$	<ul style="list-style-type: none">- MLE ↓- Robustness	<ul style="list-style-type: none">- MLT ↑
Maximum Read Range	$R_{max} : [5 \rightarrow \delta]m$	<ul style="list-style-type: none">- MLE ↓ for multi-user case- MLT ↓	<ul style="list-style-type: none">- MLE ↑ for single-user case
Positioning algorithm	S-AVG	<ul style="list-style-type: none">- Lowest complexity- Good MLE resilience as shadowing increases	<ul style="list-style-type: none">- Highest MLE- Suffers the most from all interference types
	W-AVG	<ul style="list-style-type: none">- Moderate complexity- Best performance when shadowing is high	<ul style="list-style-type: none">- When interference is high, its increased complexity over SA doesn't provide accuracy advantage
	ML	<ul style="list-style-type: none">- Best accuracy- Best MLE resilience against all interference types	<ul style="list-style-type: none">- Highest complexity- Bad performance when shadowing is high
Tag Reading activity	$\beta : [1 \rightarrow 0]$	<ul style="list-style-type: none">- MLE ↓	<ul style="list-style-type: none">- Less users are simultaneously localized

Table 2. System Design Guide.

In the absence of collisions, short read range (2 meters) is beneficial. In contrast when readers attempt simultaneously access to the medium, a higher range (3-4 meters) results in better accuracy.

To summarize, RFID technology is suitable for positioning, but its performance degrades in highly populated environments and thus a denser tag deployment or/and a mechanism for controlling reader transmissions are required.

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Radio frequency identification (RFID) is a technology that is rapidly gaining popularity due to its several benefits in a wide area of applications like inventory tracking, supply chain management, automated manufacturing, healthcare, etc. The benefits of implementing RFID technologies can be seen in terms of efficiency (increased speed in production, reduced shrinkage, lower error rates, improved asset tracking etc.) or effectiveness (services that companies provide to the customers). Leading to considerable operational and strategic benefits, RFID technology continues to bring new levels of intelligence and information, strengthening the experience of all participants in this research domain, and serving as a valuable authentication technology. We hope this book will be useful for engineers, researchers and industry personnel, and provide them with some new ideas to address current and future issues they might be facing.

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