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RFID-assisted indoor localization and the impact of interference on its performance

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ABSTRACT

Radio Frequency IDentification (RFID) is a rapidly developing wireless technology with key features which anticipate its outstanding position in the upcoming era of pervasive computing. Even though object identification is its primary objective, it is generally accepted that RFID systems can revolutionize various commercial applications. Despite its promising benefits, however, there are some technological challenges that should be addressed in order to exploit the full potential of RFID. Admittedly, the interference problem among its components and from non-conductive materials is the main shortcoming of RFID. The main goal of this paper is exploring its applicability for indoor location sensing, an important feature for the realization of ubiquitous computing applications. To that end, we study the impact of several interference types on its performance. Focusing on the case of determining the location of mobile terminals with reader extension by relying on a deployment of tags, we consider three RFID positioning schemes which are easily implemented but differ in their memory and computation requirements. Mathematical models are derived for describing the main interference types and their influence on the accuracy and time response of these schemes. Finally, extensive simulation analysis is conducted for exploring the practicality and efficacy of RFID for the localization of single or multiple users under different levels of environmental harshness. Numerical results validate the potential of RFID in location sensing but also the requirement for careful design of RFID-based positioning systems.

1. Introduction

Over the last few decades, we have been witnessing great advances in the field of wireless communications and mobile computing. RFID has a relatively long history of more than 50 years in the field of wireless communications, but 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 three basic component types, readers, tags, and servers (Want, 2006). RFID tags are simple devices with main purposes storing their ID and transmitting it to a reader. Many types of RFID tags exist, but at the highest level, they can be divided into two classes: active and passive. Active tags require a power source such as an integrated battery. Passive tags do not need a battery to operate, they just backscatter the carrier signal received from a reader. This makes their lifetime large and cost negligible. Readers are responsible for communicating with tags and an application. To that end, they have two interfaces. The first one is a RF interface enabling them to read the IDs of tags with their vicinity by running a simple link-layer protocol over the wireless channel. The second one is a communication interface, such as IEEE 802.11, for enabling communication with servers. Servers are back-end entities responsible for receiving and processing the information sent from the readers.

Key benefits of RFID, such as low cost and indefinite lifetime of passive tags, non-line of sight requirement, simultaneous and fast reading of multiple tag IDs, resilience to environmental changes, reduced sensitivity regarding user orientation, inspired the academia and industry for exploring its potentials in more intelligent applications, such as supply chain management, object or people tracking, real-time inventory, retail, anti-counterfeiting, baggage handling, and health-care (Baudin, 2005).

Nevertheless, applying RFID for indoor localization is one of the main active research domains. The localization problem has received considerable attention in the areas of pervasive computing and wireless networks as many applications need to know where objects are, and hence various location-based services (LBS), such as E911 emergency services, are being created. Furthermore, location awareness is useful for enhancing the network functionality, such as mobility management (Papapostolou and Chaouchi, 2010), quality of service support, network planning, load balancing, etc.

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While determining the location of objects in outdoor environments has been extensively studied and addressed with technologies such as GPS (Kaplan, 2005), 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 (Pahlavan and Levesque, 2005). 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 (Joshi and Kim, 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 paper, we propose deploying cheap RFID passive tags within an indoor environment in order to determine the location of users with reader-enabled mobile terminals. The rational 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. We consider three popular positioning algorithms which can be easily implemented on either the mobile or a central engine but have different processing requirements. We then study 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. The main contribution of this work, however, is modeling the RFID interference problem and providing a theoretical analysis regarding its impact on the RFID positioning performance. Finally, mechanisms for dealing with these problems are also discussed.

The organization of this paper is as follows: Section 2 provides substantial background regarding principles for wireless positioning and a literature review focusing on RFID-based indoor localization proposals. In Section 3, after modeling the communication principles among the RFID components, the conceptual framework of a RFID-based positioning system is described. In Section 4, we demonstrate and model the interference problem and its impact on RFID communication. Section 5 provides theoretical and simulation-based analysis regarding the main issues studied in this work. Finally, in Section 6 we draw our main conclusions and indicate our directions for future research.

2. Background and literature review

In this section, we first provide an overview of the localization problem and representative works. Later we review the literature for proposals relying on RFID for indoor positioning and finally we present the motivation behind our research study.

2.1. Localization at a glance

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) (Kaplan, 2005), 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 and 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 and Padmanbhan, 2000; Youssef and Agrawala, 2005; King et al., 2006; Papapostolou and Chaouchi, 2009; Ubisense), UltraWideBand (UWB) (Ingram et al., 2005), and more recently RFID (Hightower et al., 2000; Ni et al., 2003; Wang et al., 2007; Stelzer et al., 2004; Bekkali et al., 2007; Lee and Lee, 2006; Han et al., 2007; Yamano et al., 2004; Xu and Gang, 2006; Papapostolou and Chaouchi, 2009).

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 and Borriello, 2001), namely *triangulation*, *scene analysis* and *proximity*.

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 (Kaplan, 2005), 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. The Ubisense 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.

Scene analysis 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 and Padmanbhan, 2000), HORUS (Youssef and Agrawala, 2005), COMPASS (King et al., 2006) and WIFE (Papapostolou and Chaouchi, 2009) 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.

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 (Ken and Mike, 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-based localization

The benefits of RFID motivated many researchers in exploring its potential for indoor localization. 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 distances. LANDMARC (Ni et al., 2003) 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. (2007) propose a 3-D positioning scheme, namely *passive scheme*, which relies on a deployment of tags and 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 and possibly readers are deployed as reference points and their IDs are associated with their location information. In Lee and 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. (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. Yamano et al. (2004) utilize the received signal strength (RSS) to determine the reader's 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 and 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) propose also a reader localization scheme, called *active scheme*, by employing the Simplex optimization method.

Table 1 summarizes the main characteristics and performance results of the above systems, as reported by the authors.

2.3. Our motivation

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. In this paper, we focus on the second type of positioning schemes 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.

The goal of this paper is definitely not proposing a novel positioning algorithm. Actually, our motivation stems from the 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. Positioning framework

In this section, we initially model a RFID system and the communication principles among its components and later we provide the architecture and processing details of the positioning schemes we consider.

Table 1
RFID localization systems.

System	Target	Deployment	Approach	Accuracy
SpotOn (Hightower et al., 2000)	Tag	Readers	RSS trilateration	3 m
LANDMARC (Ni et al., 2003)	Tag	Readers and tags	RSS scene analysis	1–2 m
Simplex passive (Wang et al., 2007)	Tag	Readers and tags	RSS proximity and optimization	0.3–3 ft
LPM (Stelzer et al., 2004)	Tag	Readers and tags	TDOA weighted mean squares	–
Kalman (Bekkali et al., 2007)	Tag	Readers and tags	RSS mean squares and Kalman filtering	0.5–5 m
Lee (Lee and Lee, 2006)	Reader	Tags (dense)	RSS proximity	0.026 m
Han (Han et al., 2007)	Reader	Tags (dense)	Training and RSS proximity	0.016 m
SVM (Yamano et al., 2004)	Reader	Tags	RSS scene analysis	80%
Bayesian (Xu and Gang, 2006)	Reader	Tags	Proximity and Bayesian inference	1.5 m
Simplex active (Wang et al., 2007)	Reader	Tags	RSS proximity and optimization	0.2–0.5 ft

3.1. RFID system and communication model

We model an indoor environment as a 2-D area with L and W denoting its length and width, respectively. A set $\mathcal{T}$, of passive RFID tags with known coordinates $(x_t,y_t),\forall t \in \mathcal{T}$ are placed on the floor of this area such that a grid of *reference* tags is formed with inter-tag spacing δ. Within this area, we consider a set $\mathcal{U}$ of users with RFID reader-enabled terminals which are randomly located and an accurate and fast estimation of their position $(\hat{x}_u,\hat{y}_u),\forall u \in \mathcal{U}$ should be obtained.

The communication between a reader and a passive tag is done using either magnetic or electromagnetic coupling. Coupling is the transfer of energy from one medium to another medium, and tags use it to obtain power from the reader to transfer data. There are two main types of coupling, inductive and backscatter, depending on whether the tags are operating in the near-field or far-field of the interrogator, respectively. A key difference between them is that far-field communication has a longer read range compared to near field communication. RFID systems operate in the Industry, Scientific and Medical (ISM) frequency band that ranges from 100 kHz to 5.8 GHz but they are further subdivided into four categories according to their operating frequency: low frequency (LF), high frequency (HF), ultra-high frequency (UHF) and microwave. Tags operating at UHF and microwave frequencies use far-field and couple with the interrogator using backscatter. Recently, ultra-high frequency (UHF) passive RFID systems have received a great deal of attention and thus, we focus our research interest on these tag types.

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

$$PL(d) = PL_0 + 10N\log\left(\frac{d}{d_0}\right) + X_\sigma, \tag{1}$$

where d the distance between the reader and a tag, PL_0 the path loss at reference distance d_0 given by $PL_0 = G_t G_r (g_t \Gamma g_r)(\lambda/4\pi d_0)^4$ 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.

$$RSS(d) = P_t - PL(d). \tag{2}$$

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

$$R_{max} = \underset{d \geq 0}{\operatorname{argmax}} RSS(d) \geq TH, \tag{3}$$

where TH represents a threshold value for successful decoding.

Ideally, it is assumed that the signal transmission from each reader forms a circle with radius R_{max} if omnidirectional antennas are considered. However, in practice this is not real due to different signal gains at different directions. To quantify this problem a degree of irregularity (DOI) has been proposed in Wang et al. (2007), according to which if R_u and R_l the maximum and minimum values of a reader transmission range, then DOI is the maximum variation of the reader's transmission range per unit degree change.

3.2. Positioning system architecture

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.

Fig. 1 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 Section 3.3) 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.

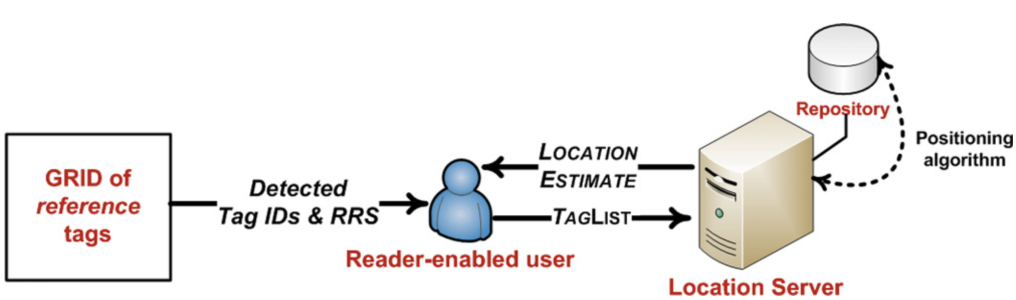

Fig. 1. Proposed RFID-based positioning architecture.

3.3. 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.

- *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.:

$$(\hat{x}_u, \hat{y}_u) = \left(\frac{\sum_{t \in \mathcal{D}_u} x_t}{|\mathcal{D}_u|}, \frac{\sum_{t \in \mathcal{D}_u} y_t}{|\mathcal{D}_u|} \right). \tag{4}$$

  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 two divisions. Therefore, it has linear complexity $O(|\mathcal{D}_u|)$.
- *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 RRS from the reader. Thus, (4) becomes

$$(\hat{x}_u, \hat{y}_u) = \left(\frac{\sum_{t \in \mathcal{D}_u} w_t \cdot x_t}{\sum_{t \in \mathcal{D}_u} w_t}, \frac{\sum_{t \in \mathcal{D}_u} w_t \cdot y_t}{\sum_{t \in \mathcal{D}_u} w_t} \right), \tag{5}$$

  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 two division operations. Thus, its complexity remains linear, i.e. $O(|\mathcal{D}_u|)$.
- *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:

$$\begin{aligned} &(x_1 - x_u)^2 + (y_1 - y_u)^2 = \hat{d}_1^2 \\ &\vdots \\ &(x_{|\mathcal{D}_u|} - x_u)^2 + (y_{|\mathcal{D}_u|} - y_u)^2 = \hat{d}_{|\mathcal{D}_u|}^2 \end{aligned} \tag{6}$$

  The above system of equations is not linear. According to Caffery (2000) 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:

$$\mathbf{A}[x_u, y_u]^T = \mathbf{b}, \tag{7}$$

  where

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

$$\mathbf{b} := \begin{pmatrix} x_1^2 - x_{|\mathcal{D}_u|}^2 + y_1^2 - y_{|\mathcal{D}_u|}^2 + \hat{d}_1^2 - \hat{d}_{|\mathcal{D}_u|}^2 \\ \vdots \\ x_{|\mathcal{D}_u|-1}^2 - x_{|\mathcal{D}_u|}^2 + y_{|\mathcal{D}_u|-1}^2 - y_{|\mathcal{D}_u|}^2 + \hat{d}_{|\mathcal{D}_u|-1}^2 - \hat{d}_{|\mathcal{D}_u|}^2 \end{pmatrix}. \tag{8}$$

  Since $\hat{d}_t$ are not accurate, the above system of equations can be solved by a standard LS approach (Caffery, 2000) as

$$[\hat{x}_u, \hat{y}_u]^T = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b} \tag{9}$$

  with the assumption that $\mathbf{A}^T\mathbf{A}$ is non-singular 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.

4. The interference problem in RFID

Even though RFID is a promising technology for localization, the interference problem should be extensively studied before the development of RFID-based localizers. In this section we demonstrate and model the main RFID interference types and their impact on the localization performance. In addition, proposed mechanisms for dealing with each type are also outlined.

4.1. 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.

4.1.1. 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 (Joshi and Kim, 2008). For instance, the EPCglobal (http://www.epcglobalinc.org), 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 (ISO/IEC, 2003). 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 with probability p which follows Poisson distribution with mean delay $1/\lambda$ between consecutive transmissions. Thus, on average each tag takes $1/|\mathcal{D}_u|\lambda$ time to transmit its ID for the first time. This is referred as arrival delay (Schwartz, 1988). 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 $(K+1)/2\times s=a$ 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 $t_{TR}=(e^{xG_A}-1)as+s+1/|\mathcal{D}_u|\lambda$. 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:

$$T_{TR}=|\mathcal{D}_u|\times t_{TR}=|\mathcal{D}_u|\times\left\{s[1+(e^{xG_A}-1)a]+\frac{1}{|\mathcal{D}_u|\lambda}\right\}. \tag{10}$$

4.2. 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

$$R_i+R_j>d_{ij} \tag{11}$$

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.

Fig. 2(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.

4.2.1. Reader collision probability

The probability P_{ij}^C of such collision type between readers r_i and r_j, if Eq. (12) 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.

$$P_{ij}^C=p_i^{scan}\times p_j^{scan}. \tag{12}$$

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

4.3. 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. Fig. 2(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.

4.3.1. Read range reduction

Reader-to-reader interference affects the read range parameter. In Eq. (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

$$R_{max}^I=\arg\max_{d\in[0,R_{max}]} SIR(d)\geq TH, \tag{13}$$

where

$$SIR(d)=\frac{P_s(d)}{\sum_i I_i} \tag{14}$$

and I_i the interference from reader r_i.

The Class 1 Gen 2 UHF standard ratified by EPCGlobal (http://www.epcglobalinc.org), separates the readers' from tags' transmissions spectrally such that tags collide only with tags and readers collide only with readers.

4.4. Interference from non-conductive materials

Since RFID technology uses electromagnetic waves for communication, interference from specific materials such as metal or water is unavoidable. This prevents tags being detected from a reader even though they are located with its zone. For incorporating this characteristic in the model, each reference tag t is assigned a probability p_t of not being detected. Obviously high values of p_t are assigned to tags which are mounted to such interfering materials.

5. Performance analysis

In this section we analyze and evaluate the performance of the studied localization schemes through simulations, using Matlab (http://www.mathworks.com) as the simulation tool. Firstly, the

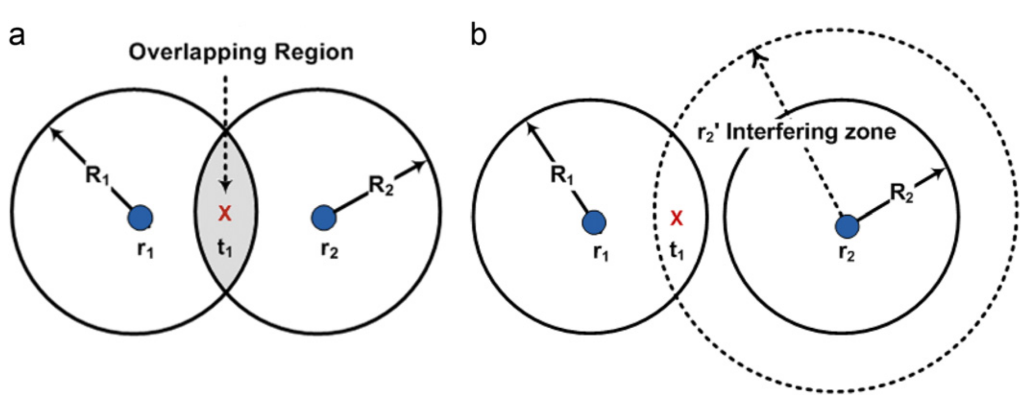

Fig. 2. Two types of interference in RFID: (a) many readers-to-tag interference and (b) reader-to-reader interference.

simulation settings are specified, then the performance objectives are defined and finally, numerical results demonstrate the behavior of RFID in localization for different system design and environment characteristics.

5.1. Simulation specifications

Table 2 summarizes the simulation parameters with their default and varied values during the performed simulations.

The simulation environment is a rectangular area $50 \times 50\,\text{m}^2$ where *reference* tags are placed in a grid fashion with inter-tag spacing δ. Within this area a set of users $\mathcal{U}$ with reader-enabled terminals are randomly located. For the UHF RFID path loss model in Eq. (1) operating frequency is 915 MHz, N=3.6 and $\sigma_2^2 \in [2,6]$.

Regarding the parameters of the Aloha anti-collision protocols we have set the rate of each tag's initial response $\lambda = 30$, the retransmission time is divided into K=5 slots and each slot duration is $s = \frac{96}{106} = 0.90\,\text{ms}$ which corresponds to the time needed for transmitting an ID of length 96 bits over a link with data rate 106 kbps.

We assume that the probability p_u^{scan} a user u's reader r_u queries for tag IDs follows uniform distribution $U(\beta,1)$, where $\beta \in [0,1]$ reflects the degree of *multiple-readers-to-tag* and *reader-to-reader* interference types. Indeed, when $\beta = 1$ all readers communicate simultaneously resulting in high level of interference, whereas when $\beta = 0$ the problems are less intense.

R_{max} denotes the maximum read range of each reader which depends on the transmit power, the decoding threshold TH, antenna gains, propagation losses, interference and fading, as shown in Eq. (14).

The probability p_t a tag t is not detected follows uniform distribution $U(0,\alpha)$, where $a \in [0,1]$ characterizes the interference degree from the material of the objects the reference tags are mounted on.

Finally, for the communication between a reader (or wireless interface) and the *location server*, the IEEE 802.11b WLAN Standard (IEEE, 1999) has been assumed with supported data rate R=2 Mbps and slot time $t_s = 20\,\mu\text{s}$. We have assumed an ideal transmission channel in terms of noise and interference and that the only cause of packet loss is due to their collisions. Collision happens when multiple nodes try to access a shared link at the same time. For wireless links, the multiple access procedure follows the IEEE 802.11 CSMA (Carrier Sense Multiple Access) mechanism. Each node senses the carrier before its transmission. If the link is busy, the node waits for a random back-off period before trying to transmit again. This back-off time follows the equation: back-off time $= CW \times t_s$, where CW represents the size of contention window in each node whose value is between CW_{min} and CW_{max}. CW_{min} and CW_{max} represent the minimum and maximum size of the contention window. After each collision, t he contention window size is doubled and the back-off time is doubled accordingly. For the 802.11b: CW_{max}=1023 and CW_{min}=31. Finally, the propagation delay T_{prop} during message transmission is less than or equal to 1 μs for the IEEE 802.11.

Table 2
Simulation parameters.

Parameter	Symbol	Default	Varied range
Area size (m^2)	$L \times W$	50×50	–
Inter-tag spacing (m)	δ	1, 2	[1,5]
# of users	$\lvert\mathcal{U}\rvert$	1, 20, 40	[1,50]
RFID frequency (MHz)	f	915	–
PL fading degree (dB)	σ^2	3.3	[2,6]
Path loss exponent	N	3.6	–
Read range (m)	R_{max}	3, 5	[3,5]
Degree of irregularity	doi	0.3	–
Tag response rate	λ	30	–
# slots/transmission time	K	5	–
Slot duration (ms)	s	0.90	–
Reader scan prob.	p^{scan}	1	$U(\beta,1) : \beta \in [0,1]$
Tag t non-detection prob.	p_t	0.1	$U(0,\alpha) : \alpha \in [0,1]$
WLAN link rate (Mbps)	R	2	
Propagation delay (μs)	T_{prop}	1	

5.2. Performance objectives

In general, the main performance objectives a positioning scheme should satisfy are high accuracy and fast time response. Thus, we define the mean location error (MLE) and mean localization time (MLT) metrics for evaluating both objectives.

MLE is measured as the Euclidean distance between the actual and the estimated positions for all $\lvert\mathcal{U}\rvert$ users, i.e.

$$\text{MLE} = \frac{1}{\lvert\mathcal{U}\rvert}\sum_{u=1}^{\lvert\mathcal{U}\rvert}\sqrt{(x_u-\hat{x}_u)^2+(y_u-\hat{y}_u)^2}. \tag{15}$$

For measuring the MLT the following time factors should be added:

1. the time T_{TR} needed for retrieving successfully all $\lvert\mathcal{D}_u\rvert$ tags' IDs within range, given by Eq. (11),
2. the time T_{R-S} needed for sending successfully the TagList message from the reader (or user terminal) to the server,
3. the processing time T_{pr} of the positioning algorithm, which depends on its complexity, and
4. the time T_{S-R} needed for sending successfully the location estimation from the server to the reader (or user terminal).

The times T_{R-S} and T_{S-R} include the transmission delay T_{tr}, the collision delay T_{col} for accessing the wireless medium and the propagation delay T_{prop}. The transmission delay T_{tr} depends on the message size in bits and the link rate R. For instance, the TagList message includes mainly $\lvert\mathcal{D}_u\rvert \times 96$ bits. The timestamp and some additional control bits are ignored. Thus,

$$T_{tr}^{R-S} \approx \frac{96 \times \lvert\mathcal{D}_u\rvert}{2 \times 10^6} = 48 \times \lvert\mathcal{D}_u\rvert\,\mu\text{s}. \tag{16}$$

The collision delay depends on the anti-collision protocol. For instance, for the IEEE 802.11b CSMA mechanism, the mean collision delay is given by

$$T_{col} = \frac{CW_{max}-CW_{min}}{2} \times t_s = 10\,\text{ms}. \tag{17}$$

5.3. Numerical results

Numerical results based on the average of 1000 independent simulation executions are presented in the following. We first focus on the single-user case and study the impact of several system design and environmental parameters on the positioning performance. In the sequence, we consider the case of multiple co-located users in order to manifest the accuracy degradation due to the several interference types. Finally, we show that this performance degradation can be compensated if the interference problem is alleviated or solved.

5.3.1. Single-user case

The principal parameters related to the design of the proposed RFID-based positioning system are the inter-tag spacing δ of the *reference* tags, the maximum read range R_{max} of the readers, the positioning algorithm (SA, WA or ML) and the anti-collision algorithm (PA or SA).

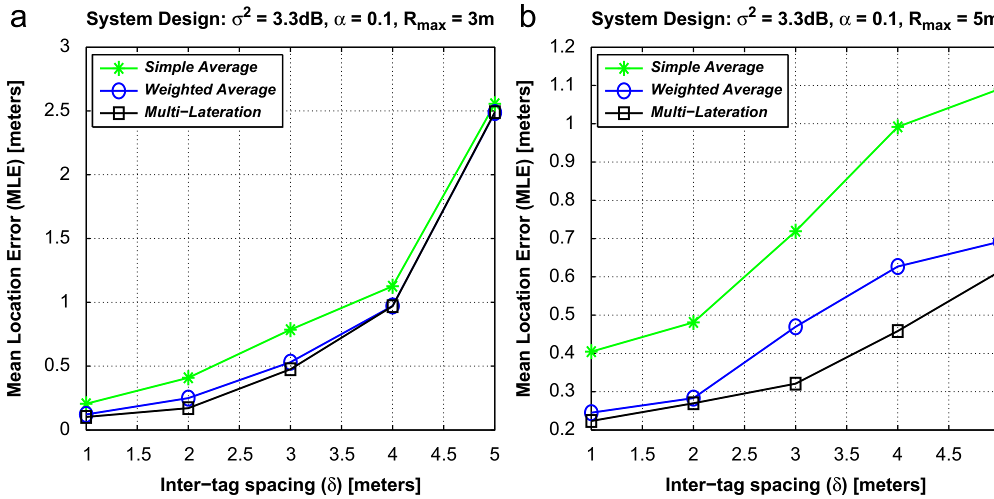

Fig. 3. Impact of system design parameters on *accuracy* for a single user: (a) MLE vs. inter-tag spacing δ when R_{max}=3 m and (b) MLE vs. inter-tag spacing δ when R_{max}=5 m.

The environmental parameters characterize the severity of the indoor space. For our model, the main such tuning parameters are the fading degree σ^2 in Eq. (1) and the parameter α of the Uniform probability distribution function $U(a,1)$ followed by $p_t, \forall t \in \mathcal{T}$.

Fig. 3 illustrates the dependency of the positioning accuracy on the inter-tag spacing δ and the three positioning algorithms when R_{max}=3 m in Fig. 3(a) and R_{max}=5 m in Fig. 3(b). The main observation is that for all cases, increasing the inter-tag spacing δ reduces the positioning accuracy, which is quite rational since less tags are detected by each reader. Comparing the three positioning algorithms, we remark that considering the RSS information and increasing the processing complexity results in better accuracy, especially when R_{max}=5 m. Regarding the two cases of the maximum read range, we observe that for $\delta \leq 2$ m both of them achieve low MLE less than 0.5 m. However, for $\delta \geq 3$ m when R_{max}=3 m the accuracy reduction is much higher. This is because fewer tags are detected when the read range is reduced. On the other hand, when R_{max}=5 m achieving high accuracy does not require a dense tag deployment ($\delta \geq 4$ m), especially when the WA or ML techniques are followed.

In Fig. 4 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 Eq. (11) 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 algorithms when R_{max}=3 and 5 m is depicted in Fig. 4(a) and (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}=3 m less tags are within a reader's interrogation zone and thus, less reading time is required. Finally, recalling Fig. 3, 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 depicts the processing time T_{pr} (specified in flops[1]) of each positioning algorithm as the inter-tag spacing increases, for R_{max}=3 and 5 m in Figs. 5(a) and (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 Fig. 3(b) is taken into account. The WA approach has the best performance if both objectives are considered. Moreover, for R_{max}=5 m and $\delta = 5$ m, the accuracy of the ML technique is high without considerable processing cost. Therefore, more sophisticated techniques can alleviate the need for carefully designed systems.

In general, the accuracy of indoor wireless positioning depends also on the characteristics of the environment. In Fig. 6 we examine the impact of the fading degree σ^2 and the interference level α from materials on the MLE for the three positioning algorithms. Regarding the fading level in Fig. 6(a), we observe that the SA and WA positioning algorithms exhibit tolerance regardless the increase of σ^2, whereas the performance of the ML technique is greatly degraded. This is because ML's accuracy depends highly on the accuracy of the path loss model which is used for estimating the distance from each detected tag. On the other hand, the location coordinates of the detected tags are the principal factors for the SA and WA algorithms. Fig. 6(b) depicts the MLE increase due to the interference rise from non-conductive materials as α increases. This factor is especially detrimental for the SA and WA algorithms, while the ML exhibits great tolerance. This is because in ML, detecting three tags is enough for accurate location estimation.

5.3.2. Multi-user case

So far, we were considering only one user being randomly located in the indoor space and we were exploring the performance of RFID positioning. In the following, we consider the case of multiple co-located users and we repeat similar performance tests in order to manifest the accuracy reduction caused due to their interference.

[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) (Chapra, 2002).

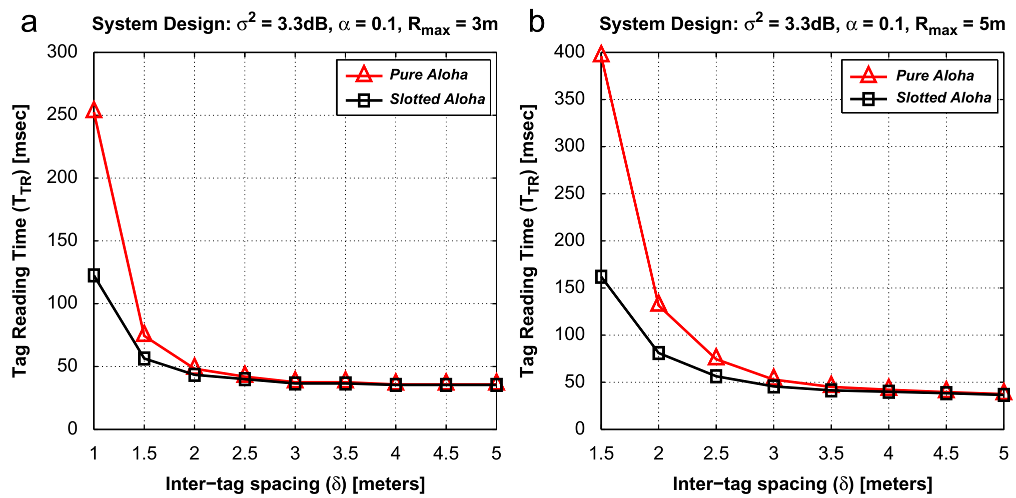

Fig. 4. Impact of system design parameters on *time response*: (a) tag reading time vs. inter-tag spacing when $R_{max} = 3$ m and (b) tag reading time vs. inter-tag spacing when $R_{max} = 5$ m.

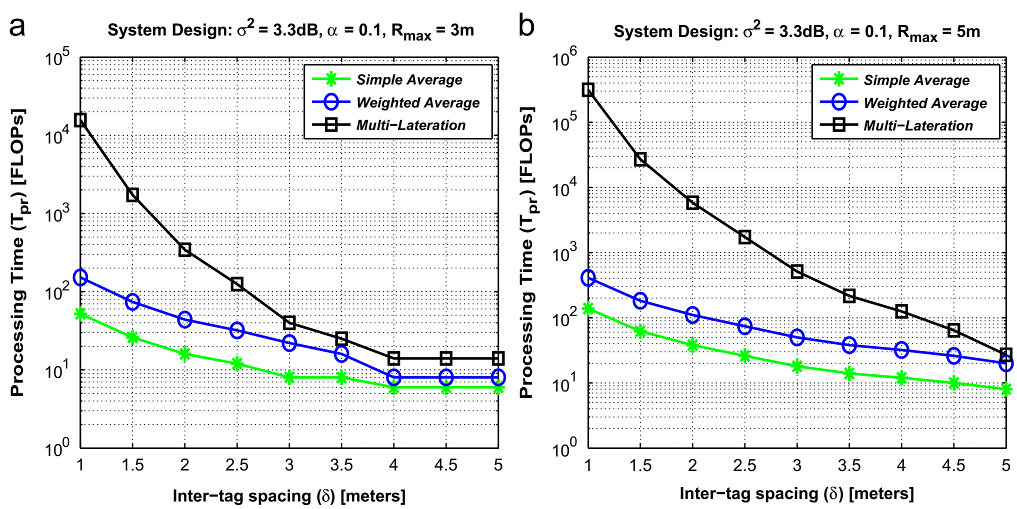

Fig. 5. Impact of positioning algorithm on *time response*: (a) processing time vs. inter-tag spacing when $R_{max} = 3$ m and (b) processing time vs. inter-tag spacing when $R_{max} = 5$ m.

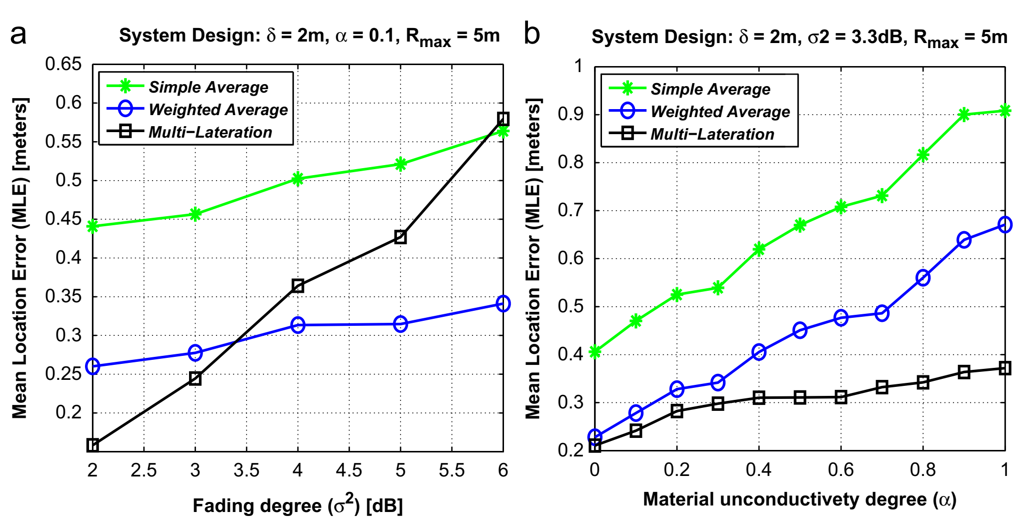

Fig. 6. Impact of environmental parameters on *accuracy* for a single user: (a) MLE vs. fading degree σ^2 and (b) MLE vs. interference level from materials α.

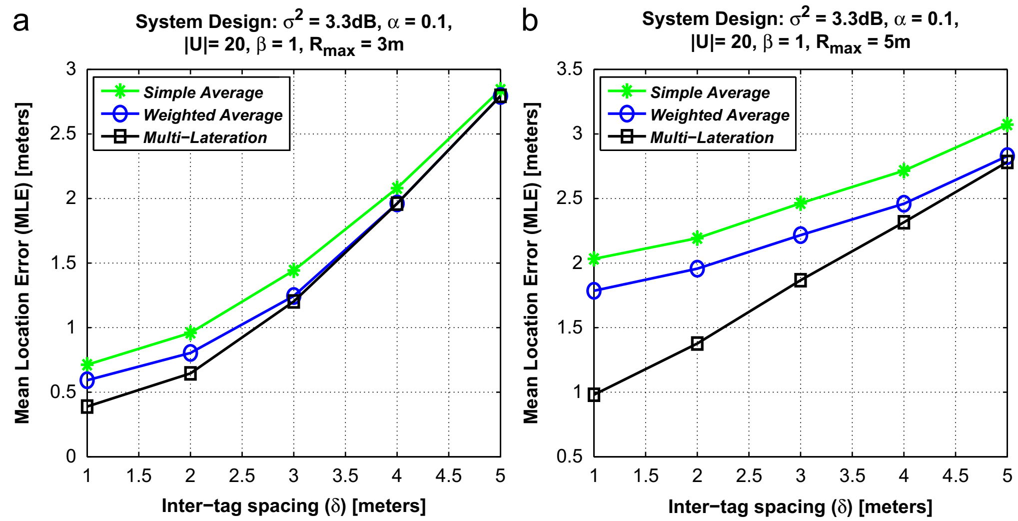

Fig. 7. Impact of system design parameters on *accuracy* for multiple users: (a) MLE vs. inter-tag spacing δ when $R_{max}=3$ m and (b) MLE vs. inter-tag spacing δ when $R_{max}=5$ m.

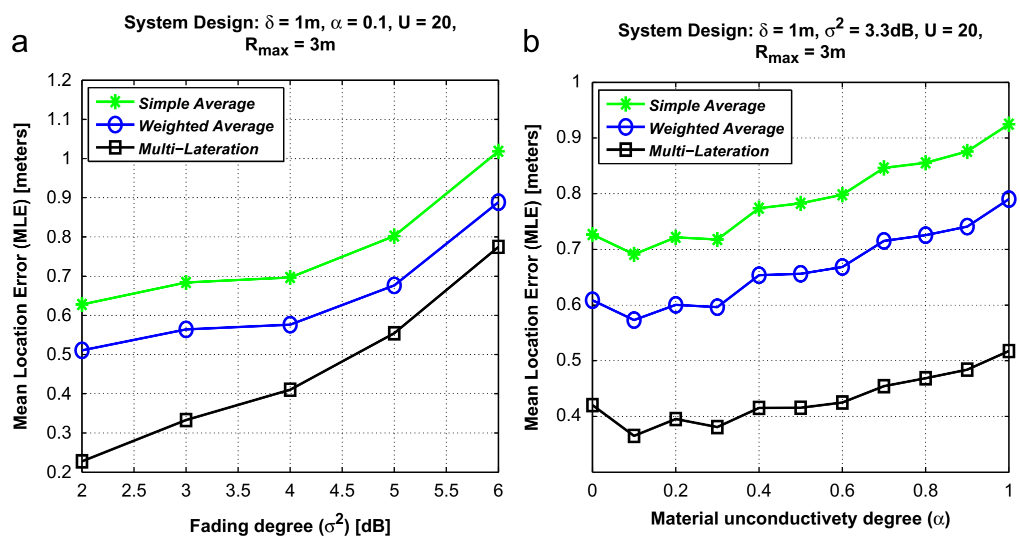

Fig. 8. Impact of environmental parameters on *accuracy* for multiple users: (a) MLE vs. fading degree σ^2 and (b) MLE vs. interference level from materials α.

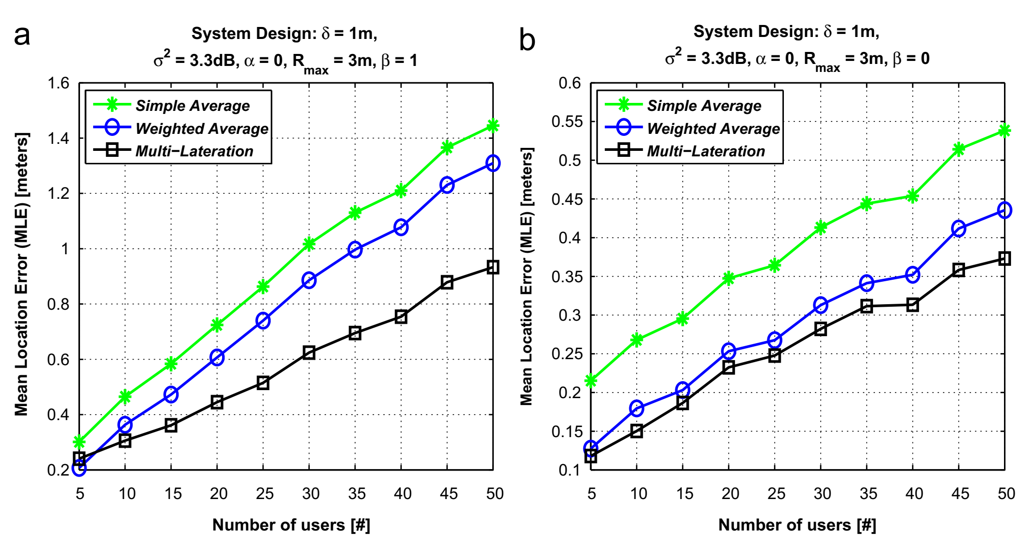

Fig. 9. Accuracy reduction due to users' increase and its potential alleviation: (a) MLE vs. number of users $|\mathcal{U}|$ when $\beta=1$ and (b) MLE vs. number of users $|\mathcal{U}|$ when $\beta=0$.

Fig. 7 is the corresponding of Fig. 3 but for $|\mathcal{U}|=20$ users whose positions need to be determined simultaneously, i.e. $\beta=1$. Our remarks regarding the impact of the tag density δ and the positioning algorithms are validated for this case as well. However, compared to the single-user case, now there is a noticeable accuracy decay which demonstrates the impairing impact of the interference problem in RFID. Furthermore, while in the single-user case $R_{max}=5$ m was providing higher accuracy, in this case setting $R_{max}=3$ m is more beneficent. This is obvious due to the higher probability of overlap among several read zones. Besides these observations, an interesting conclusion that can be made is that by adjusting the reader's range through a power control or another mechanism can alleviate the problem.

Fig. 8 is the corresponding of Fig. 6 but for $|\mathcal{U}|=20$ users, $\delta=1$ m instead of $\delta=2$ m and $R_{max}=3$ m instead of $R_{max}=5$ m. The main observation is that the interference problem makes the deteriorating impact of both environmental factors on the accuracy even more harmful. The most interesting remark, however, concerns the behavior of the ML technique in the presence of severe fading. We notice that while in the single-user case (Fig. 6(a)) it has worse performance than the WA and almost the same with the SA, in the multi-user case (Fig. 8(a)) it is superior. This indicates that ML can combat the interference problem more efficiently than the other schemes. However, this comes with higher complexity cost.

In the following we focus on the main parameters which affect the level of interference, i.e. the number of users $|\mathcal{U}|$, the read range R_{max} and the scanning probability of their reader which is modelled by the parameter β.

In Figs. 9(a) and (b) we show the impact of increasing the number of users $|\mathcal{U}|$ when $\beta=1$ and 0, respectively. Obviously, the MLE increases with the users' population expansion. The remarkable notice, however, is that for $\beta=0$ the accuracy reduction is less. Therefore, if a mechanism for coordinating reader transmissions is designed, the accuracy degradation due to the RFID interference problem can be compensated.

In Figs. 10(a) and (b) we show the impact of the reader range R_{max} when $\beta=1$ and 0, respectively, for $|\mathcal{U}|=40$ users. As expected, as R_{max} grows the MLE increases due to the higher probability of overlap among readers' interrogation zones.

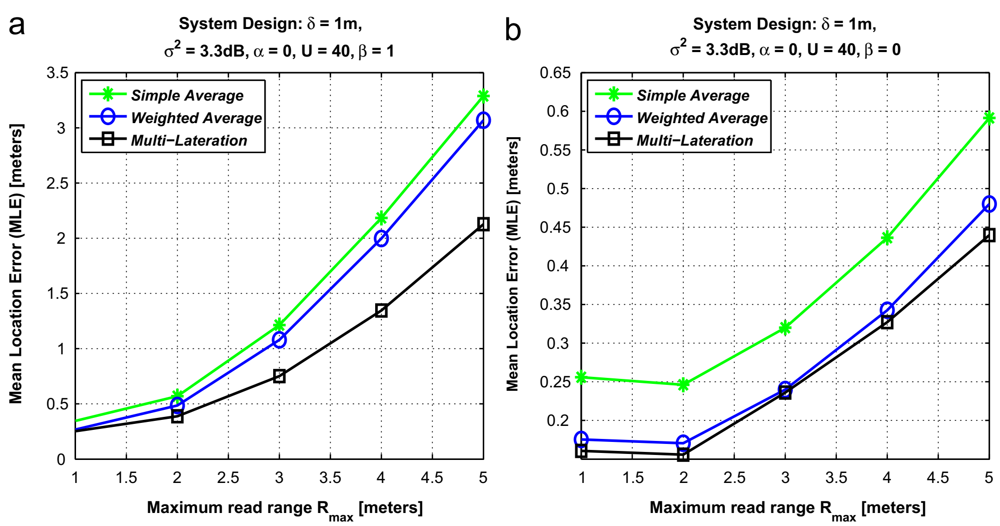

Fig. 10. Accuracy reduction due to read range increase and its potential alleviation: (a) MLE vs. read range R_{max} when $\beta=1$ and (b) MLE vs. read range R_{max} when $\beta=0$.

Table 3
System design guide.

Design parameter		Pros	Cons
Reference tag deployment	$\delta:[5\rightarrow 1]m$	• MLE ↓ • Robustness as interference or environmental harshness increases	• MLT ↑
Maximum read range	$R_{max}:[5\rightarrow \delta]m$	• MLE ↓ for multi-user case • MLT ↓	•MLE ↑ for single-user case
Positioning algorithm	SA	• Lowest complexity	• Highest MLE
	WA	• Good MLE resilience as fading increases • Moderate complexity	• Suffers the most from all interference types • When interference is high, its increased complexity over SA does not provide accuracy advantage
	ML	• Best performance when fading is high • Best accuracy • Best MLE resilience against all interference types	• Highest complexity • Bad performance when fading is high
Tag reading activity	$\beta:[1\rightarrow 0]$	• MLE ↓	• Less users are simultaneously localized

However, the interference intensity can be greatly alleviated if readers' transmissions are coordinated.

Finally in Table 3 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. Conclusions

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 paper, this issue is mainly addressed. After modeling the interference problem in RFID by considering its technology and communication specifications, we conduct extensive simulations for analyzing the performance of RFID in tracking single or multiple users, under different system configurations and environmental conditions. Numerical results encourage adopting RFID for localization but also indicate the essentiality of a careful system design in order to exploit its full potential, especially for highly populated environments.

As future work we plan validating our analysis using different simulation tools such as NS-2 (http://www.isi.edu/nsnam/ns/) or RFIDSIM (Balakrishnan and Krishnan) and in real experimental testbeds.

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