Indoor Localization Using Passive RFID

George E. Vastianos, Dimitris M. Kyriazanos, Olga E. Segou,
Stelios A. Mitilineos and Stelios C. A. Thomopoulos
NCSR "Demokritos", Institute of Informatics and Telecommunications, Athens, Greece
{gvastian, dkyri, osegou, stelmit, scat}@iit.demokritos.gr

ABSTRACT

Radio frequency identification (RFID) systems based on passive tags are used successfully in a wide range of object identification applications. However, the increasing needs to meet new demands on applications of localization and tracking create a new field for evolution of the RFID technology. This paper presents the design, implementation, and evaluation of a cost-effective localization system for in-building usage that is able to localize objects that carry passive RFID tags. The RFID reading is performed by a single Reader and an array of directional antennas through multiplexing. Evaluation and experimental results from three localization algorithms based on RSSI are presented.

Keywords: Localization, RFID, Multiplexing, Received Signal Strength, Fingerprinting, Cell-ID

1. INTRODUCTION

The knowledge of location of users, equipment or items is a prerequisite for the support of context-aware applications. Localization of physical objects is in itself a distinct research area that involves the development of localization hardware devices, software storage structures, and mechanisms to enable location-based querying. Localization devices may give a location directly, such as in case of GPS receivers or can also take the form of a tag, attached to a user or device that periodically communicates with a fixed receiving infrastructure [1]. In the latter case, knowledge of the location of receiving devices in collaboration with various algorithms can lead to the determination of the locations of the tagged objects.

Radio Frequency Identification (RFID) is an electronic tagging technology that allows automatic objects identification at a distance using an electromagnetic based challenge-and-response exchange of data [2]. By attaching Radio Frequency (RF) tags to objects, RFID technologies enable various applications such as supply chain management [3], transportation payment, warehouse operations [4], library management [5], and so on. Recently, new types of RFID based applications such as activity monitoring and localization have been proposed [6].

RFID systems consist of RF readers and RF tags. Tags can be classified into two types, active and passive. An active tag contains a radio transceiver and its own power source while a passive tag exchanges data with the reader through an electromagnetic challenge-and-response coupling without the need of battery. Active tags are, in general, expensive and not suitable for applications that require large number of tags. On the other hand the fact that passive tags require no battery, makes them relatively inexpensive and affordable for large-scale deployment. By attaching RFID tags to objects, it becomes possible to detect their presence from short to relatively long range especially if the tags communicate within the UHF frequency band. Aside from the cost of tags, the major factor that defines the total cost of an application is the type and number of RFID readers. Specific types of applications, like localization, require a relatively significant number of receiving ends, e.g. readers, in order to compare and process readings of a tag from different reference points and finally calculate its position. Taking into account that a mediocre UHF reader costs some hundreds of US$, we can easily assume that a small to medium scale localization application will cost so much that finally may become completely cost-ineffective for its purpose.

The approach we present in this paper fills in the existing gap in localization with passive RFID by introducing a very cost-effective solution based on passive tags, a single reader, and an array of nine multiplexed directional antennas that are illuminated by the reader in a round-robin fashion. This combination creates a nine-cell localization system that costs only 15% of the price of a system with the same cell number-size based on "one reader-per-cell" approach. The proposed system has been tested in real conditions in two different environments. For the evaluation of the system, three

Signal Processing, Sensor Fusion, and Target Recognition XX, edited by Ivan Kadar,
Proc. of SPIE Vol. 8050, 80501R · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.887036

localization algorithms were used based on Fingerprinting and Cell-ID methodologies that make use of the Received Signal Strength (RSS) information.

2. SYSTEM ARCHITECTURE

2.1 Overall architecture

The proposed system consists of a group of hardware and software components that are interconnected with each other in a complex way. A highly simplified description of the overall architecture that combines the hardware and software modules is presented in Figure 1.

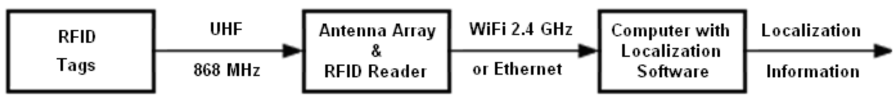


Figure 1. Simplified version of the localization system architecture.

In Figure 1, the RFID tags have been placed in various locations inside the working area of the system. An RFID reader in collaboration with an antenna array is able to communicate and read the RFID tags through RF signals at 868 MHz. The RFID reader is remotely controlled by a computer via wireless LAN on 2.4 GHz or Ethernet. The remote computer is equipped with the appropriate software that runs the localization algorithms and outputs the location information of each RFID tag to the application layer of the system. The system architecture consists of various hardware and software components that cannot all be included in a simplified, high-level description of the architecture as in Figure 1. The hardware and software architectures inside the localization system are discussed in subsections 2.2 and 2.3 respectively.

2.2 Hardware architecture

Figure 2 depicts a schematic representation of the system based on an analysis of its hardware components.

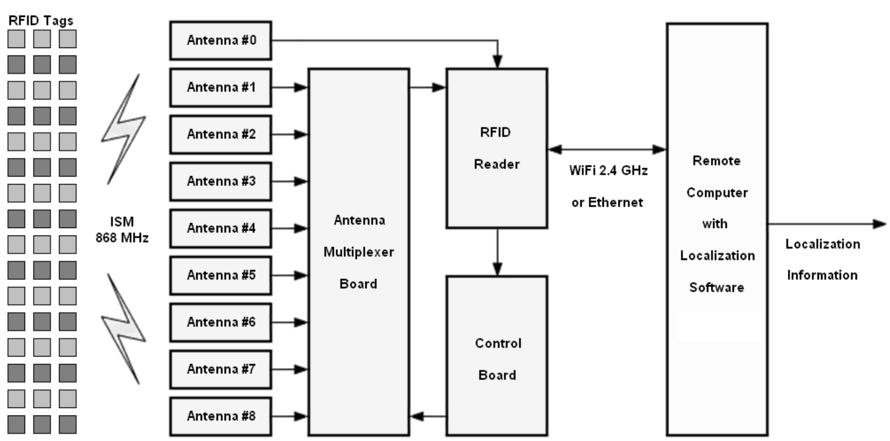


Figure 2. Hardware components of the RFID localization system.

In Figure 2, the RFID tags have been placed in various locations inside the working area of the system. The used RFID tags are "Allien Squiggle", Class1 Gen2 type RFIDs and as working area we define the area that corresponds to the superset of all nine antennas individual coverage areas operating at 868 MHz ISM band. All antennas are circularly polarized wideband RFID panel Antennas and have been manufactured by Laird Technologies (S8658WPR) for operation at the 868MHz ISM band. The first antenna (#0) is the embedded antenna of the RFID reader while the rest eight (#1-#8) are connected with low loss coaxial cables to the Antenna Multiplexer Board that is constructed by Skyetek (SkyePlus MXU). The multiplexer board is connected to an integrated RFID reader manufactured by ThingMagic (Astra) and gives the reader the ability to be connected with the eight antennas of the nine-antenna array through the Control Board designed and built in house by NCSR "Demokritos". The Antenna Multiplexer Board and the Control Board have been integrated to a single device as an Antenna Multiplexer Unit that lies in the middle between the antenna array and the RFID reader. The RFID reader is connected with a remote computer that runs the localization algorithms and outputs the location data of each RFID tag (to the application layer of the system) through an Ethernet or a 2.4 GHz WiFi infrastructure. Pictures of the hardware components of the RFID localization system are shown in Figure 3.

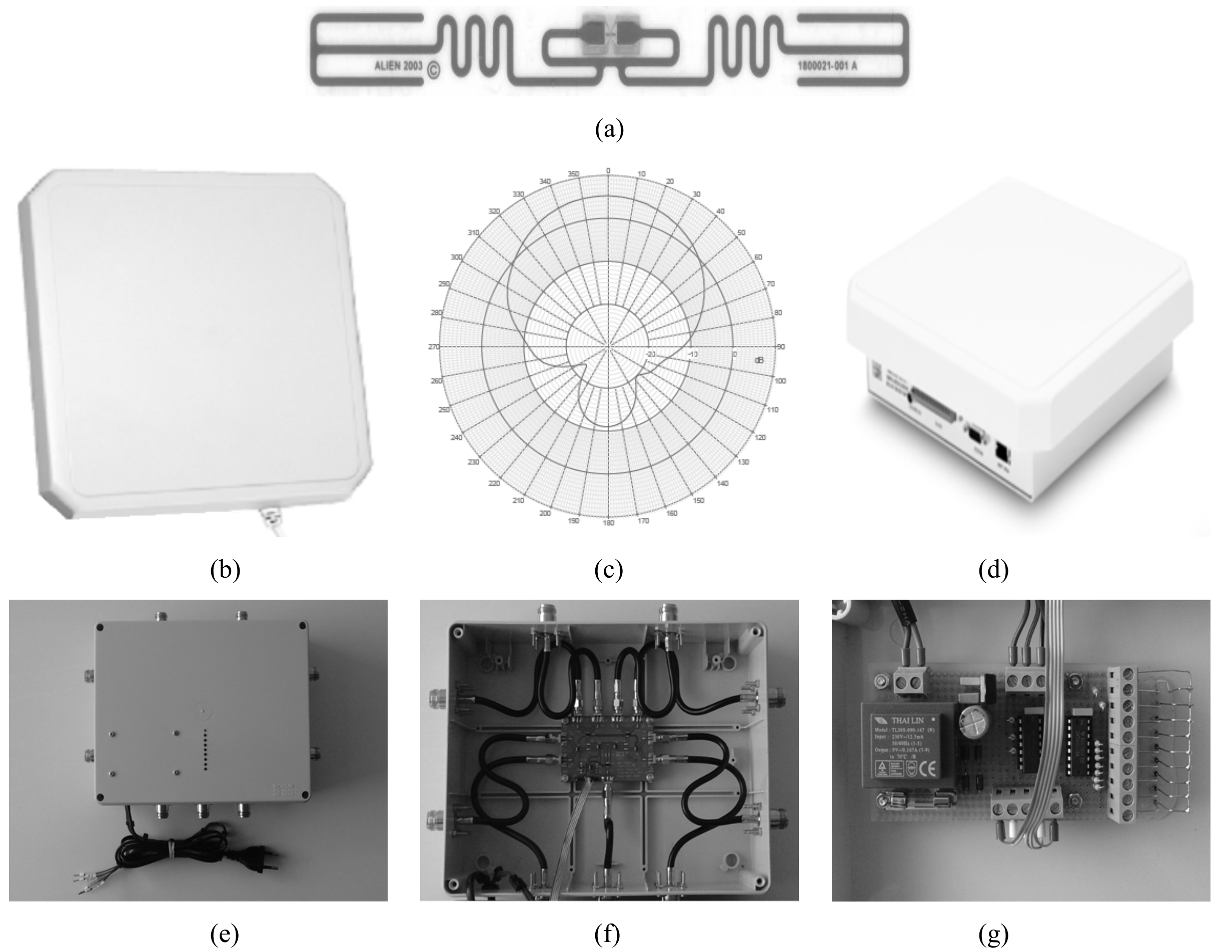


Figure 3. Hardware components of the passive RFID localization system (from top center to down right): (a) The Alien Squigle RFID Tag; (b) The S8658WPR Antenna; (c) S8658WPR Antenna Radiation Pattern; (d) Astra RFID Reader; (e) The Antenna Multiplexer Unit; (f) SkyePlus MXU Multiplexer & RF Connectors; and (g) Control Board & LED Indicators.

2.3 Software architecture

The software components architecture in the RFID localization system is illustrated in Figure 4.

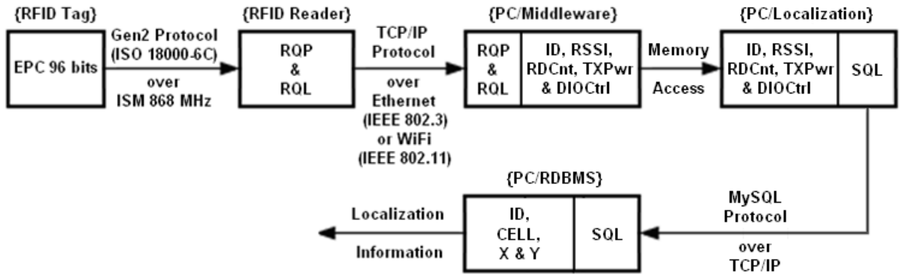


Figure 4. Software architecture components of the RFID localization system.

In Figure 4, the RFID tags contain an ID serial number 96 bits long stored in their EPC memory. The RFID reader in collaboration with the multiplexer and the antennas array (as described above) can communicate with the RFID tags through RF on 868 MHz via the Gen2 Protocol (ISO 18000-6C). The RFID reader and the remote computer that runs the localization algorithms are connected with TCP/IP protocol over Ethernet (IEEE 802.3), or WiFi on 2.4 GHz (IEEE 802.11). The reader and the computer exchange RFID data through an SQL like language called RQL (Reader Query Language) that is transferred via the RQP (Reader Query Protocol) that works as an application protocol over TCP/IP. On remote computer's side the Middleware software component uses RQL and RQP to exchange with the reader application level RFID data (per tag) such as ID, RSSI, ReadCounts and special reader commands such as Transmit Power and Digital I/O Control (for multiplexer operation). This data is transferred to the Localization software component that runs the localization algorithms through memory access. The calculated positions of each tag ID (expressed as X, Y and Cell-ID) are stored to a Relational Database Management System server (MySQL) for retrieval from the application layer of the end system. The Localization component communicates with the RDBMS server through SQL language via the MySQL protocol over TCP/IP. The Middleware and Localization software components have been developed by NCSR "Demokritos".

3. LOCALIZATION ALGORITHMS

3.1 Fingerprinting algorithm

For localization based on the fingerprinting method [7], [8], two vectors are normally used in estimating the location of an RFID tag. The first vector consists of the sample RSSI measurements of the tag from the n antennas of the system $(n=9)$ and is denoted as $\vec{R}=[\rho_1,\rho_2,...,\rho_n]$. The indoor positioning system estimates the tag's location using this *sample RSSI vector*. Each component in this vector is assumed to be a random variable that is mutually independent and normally (or Gaussian) distributed. The (sample) standard deviation of all the random variables ρ_i is assumed to be identical and denoted by σ. The true mean of the random variable ρ_i or $E\{\rho_i\}$ is denoted as r_i. The second vector, that forms the fingerprint of the location, consists of the true means of all the received signal strength random variables at a particular location from the n antennas of the system and is recorded in the location database. This vector is called *location fingerprint* or *average RSSI vector* and is denoted by $\vec{F}=[r_1,r_2,...,r_n]$. To determine which of the location fingerprint points correspond to the location of the tag, the *signal distance* between the sample RSSI vector and the average RSSI vectors is used. This method selects the (x,y) coordinates corresponding to the average RSSI vector with the smallest signal distance to the sample RSSI vector as the estimated location. The distance between the two vectors is the *Euclidean distance* z between $\vec{F}$ and $\vec{R}$ is given by:

$$z=\left(\sum_{i=1}^{n}(\rho_i-r_i)^2\right)^{\frac{1}{2}} \tag{1}$$

Assuming we are using k minimum *Euclidean distances* to estimate the tag's position, then x_{est} and y_{est} are given by:

$$x_{est} = \frac{\sum_{i=1}^{k} \frac{x_i}{z_i}}{\sum_{i=1}^{k} \frac{1}{z_i}}, \; y_{est} = \frac{\sum_{i=1}^{k} \frac{y_i}{z_i}}{\sum_{i=1}^{k} \frac{1}{z_i}} \quad (2,3)$$

For the measurements of the *sample RSSI vector* and *average RSSI vectors,* it is implied that the transmitting power of the RFID reader remains constant.

3.2 Cell-ID algorithm

The simplest implementation of an RSSI based Cell-ID localization algorithm consists of a vector with sample RSSI measurements from n antennas that is denoted as $\vec{R} = [\rho_1, \rho_2, ..., \rho_n]$ and the random ρ_i variable's index with the highest value is equal to the index of the cell that includes the tag. In this case the estimated position of the tag is assumed to be the center of the cell. Early experiments with passive RFID tags and this simple Cell-ID approach have shown that there are rare cases where high levels of radiated power from the reader produce saturation effects to the tags and make them respond with lower transmission power. The results of these rare incidents may lead to wrong cell estimation where the RSSI measurement value of the tag's cell is the same or even lower than the RSSI values of the neighbor cells. In order to minimize the probability of this effect and increase the overall *precision* of the algorithm, an advanced Cell-ID algorithm was developed based on the *RSSI*, *Transmitted Power* and *Read Count* variables. As *Read Count* we define the number of successful readings of a tag for a predefined period of time and a constant *Transmitted Power* from reader that produces an average *RSSI* measurement. Assuming that we use n number of antennas-cells and the scan procedure is executed on k levels of transmitting power then the advanced Cell-ID algorithm will use as input two 2-d vectors ($\vec{R}$, $\vec{C}$) with $k*n$ size that will include the data of the RSSI and ReadCount random variables (ρ , c):

$$\vec{R} = \begin{bmatrix} \rho_{1,1}, \rho_{1,2}, ..., \rho_{1,n} \\ \rho_{2,1}, \rho_{2,2}, ..., \rho_{2,n} \\ ... \\ \rho_{k,1}, \rho_{k,2}, ..., \rho_{k,n} \end{bmatrix}, \; \vec{C} = \begin{bmatrix} c_{1,1}, c_{1,2}, ..., c_{1,n} \\ c_{2,1}, c_{2,2}, ..., c_{2,n} \\ ... \\ c_{k,1}, c_{k,2}, ..., c_{k,n} \end{bmatrix} \quad (4,5)$$

From the components of the $\vec{R}$ vector (4), three supplementary vectors ($\vec{M}$, $\vec{Ms}$, $\vec{Mm}$) are produced that help us to find the cell with the highest signal strength rating. The $\vec{M}$ (6) is a 2-d vector with $k*n$ size that shows the maximum signal strength components of $\vec{R}$ (per transmitted power level) and the $\vec{Ms}$ (7) is a 1-d vector with n size that shows the total maximum component ratings per cell (on all transmitted power levels). Also $\vec{Mm}$ (8) is a 1-d vector with n components derived from $\vec{Ms}$ that shows the cell(s) with the overall highest signal strength rating. The $\vec{M}$, $\vec{Ms}$, $\vec{Mm}$ components are defined as follows:

$$M_{i,j} = \begin{cases} 1, R_{i,j} = \max_{j=1}^{n} R_{i,j} \\ 0, R_{i,j} \neq \max_{j=1}^{n} R_{i,j} \end{cases}, \; \vec{Ms} = \left[\sum_{i=1}^{k} M_{i,1}, \sum_{i=1}^{k} M_{i,2}, ..., \sum_{i=1}^{k} M_{i,n} \right], \; Mm_i = \begin{cases} 1, Ms_i = \max_{i=1}^{n} Ms_i \\ 0, Ms_i \neq \max_{i=1}^{n} Ms_i \end{cases} \quad (6,7,8)$$

In order to minimize the probability of a non-unique result when two or more cells have simultaneously the highest signal strength rating, the data of a ReadCount random variable ρ is used to make the cell-decision of the algorithm more robust. From the $\vec{C}$ vector, the $\vec{Cs}$ vector in (9) with n components is derived, and shows the total ReadCount ratings per cell (on all transmitted power levels). The final cell-decision is extracted from the $\vec{X}$ vector (10), where its components are derived from the multiplication of $\vec{Mm}$ with the $\vec{Cs}$ components, and the Cell-ID is the index of the $\vec{X}$

highest value component (11). As already described above, the estimated tag position (x_{est}, y_{est}) is equal to the coordinates of the Cell-ID center.

$$\vec{Cs} = \left[\sum_{i=1}^{k} C_{i,1}, \sum_{i=1}^{k} C_{i,2}, ..., \sum_{i=1}^{k} C_{i,n} \right], \; X_i = Mm_i * Cs_i \,, \; Cell = \{ i, X_i = \max_{i=1}^{n} X_i \qquad (9,10,11)$$

3.3 Combined Fingerprinting with Cell-ID algorithm

Early experiments using the algorithms described above have shown that the advanced Cell-ID is performing better than the fingerprinting method in the testbeds they were tested. The combined fingerprinting with Cell-ID algorithm is the result of an attempt to improve the accuracy of the fingerprinting by leveraging the superior performance of Cell-ID. This advanced Cell-ID algorithm is executed in two steps: In step one, the advanced Cell-ID is executed and the result is used as input to the second step. In step two, the fingerprinting algorithm is executed by taking into account the average RSSI input from those fingerprints whose location belongs to the coverage area of the cell detected during step one.

4. EVALUATION PROCESS & RESULTS

4.1 Experiment runs and evaluation parameters

The developed passive RFID localization system was installed and tested in two different testbeds. The first testbed was the LocTrack Lab of NCSR "Demokritos" in Athens, Greece (Figure 5a). The covered area was $21m^2$ (3.5x6) with 9 used cells with coordinates (1.1,2.2), (0.1,4.0), (0.1,2.2), (0.1,0.4), (1.45,-0.2), (3.0,0.4), (3.0,2.2), (3.0,4.0), (1.45,4.6). Measurements were taken on 21 random positions and analyzed with 0.5 m fingerprints grid step (FGS) with 104 fingerprints and 1.0 m fingerprints grid step (FGS) with 28 fingerprints. The second testbed was the Homelab of Tecnalia (Health and Quality of Life Unit) in Bilbao, Spain (Figure 5b). The covered area was 30 m^2 (5x6) with 9 used cells with coordinates (3.0,2.75), (3.5,0.75), (5.25,1.25), (6.0,3.75), (5.25,4.75), (3.5,5.25), (2.0,4.5), (3.0,1.5), (2.0,1.75). Measurements were taken on 21 random positions and analyzed with 0.5 m fingerprints grid step (FGS) with 138 fingerprints and 1.0 m fingerprints grid step (FGS) with 39 fingerprints. The transmitted power used in both installations was 30dbm for the fingerprinting algorithm and 21dbm to 30dbm (10 power levels) for the advanced Cell-ID and combined algorithms.

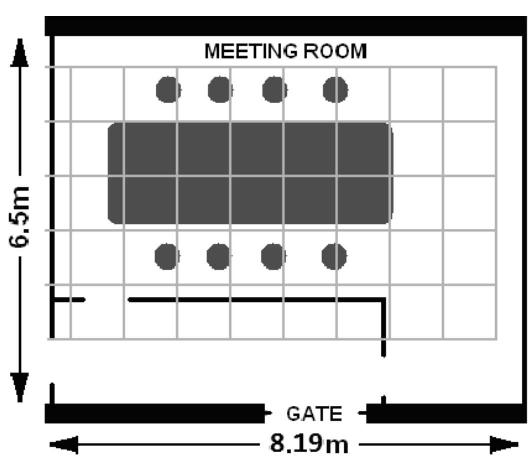


Figure 5a. LocTrack Lab of NCSR "Demokritos".

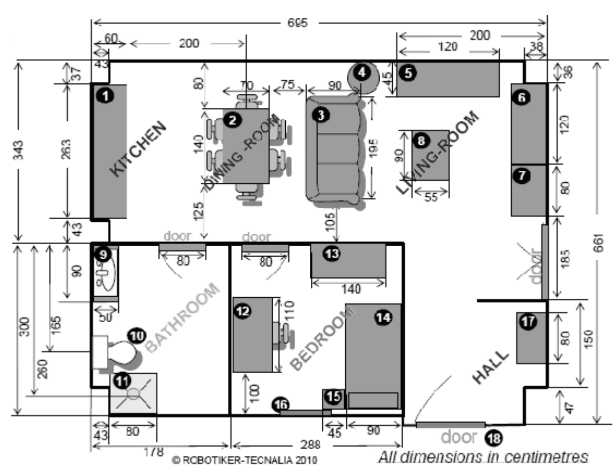


Figure 5b. HomeLab of Tecnalia (H&QoL Unit) [9].

A ceiling view of the Passive RFID Localization System as installed and tested in Tecnalia (Health and Quality of Life Unit) HomeLab testbed in Bilbao, Spain, is shown in Figure 6 (courtesy of Tecnalia [9];). Seen in Figure 6 are: (a) (in the upper right corner) the central antenna, controller unit and multiplexer; and (b) (multiplexed with cables out of the multiplexer) three out of the eight panel antennas (the other five are installed in the "bedroom", "bathroom" and "kitchen" of the testbed facility and not shown).

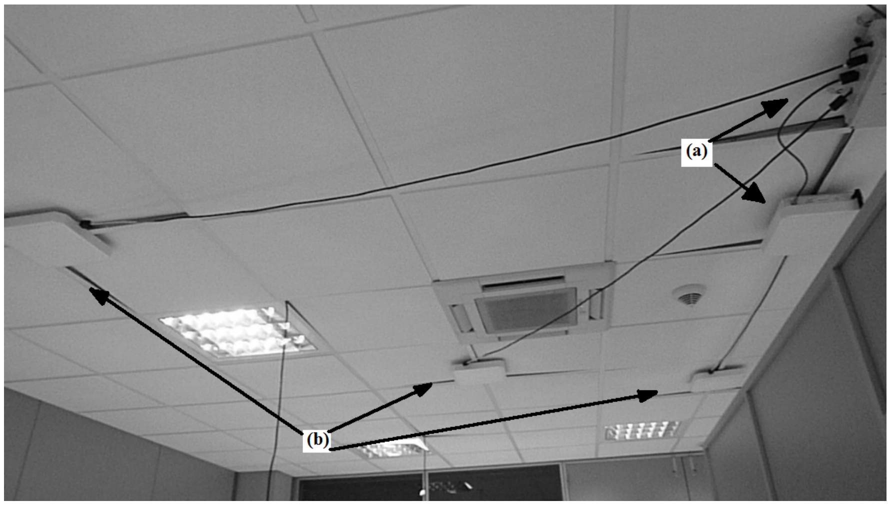


Figure 6: A ceiling view of the Passive RFID Localization System as installed and tested in Tecnalia (Health and Quality of Life Unit) HomeLab testbed in Bilbao, Spain. Shown are: (a) the central antenna, controller unit and multiplexer; and (b) three out of the eight multiplexed panel antennas.

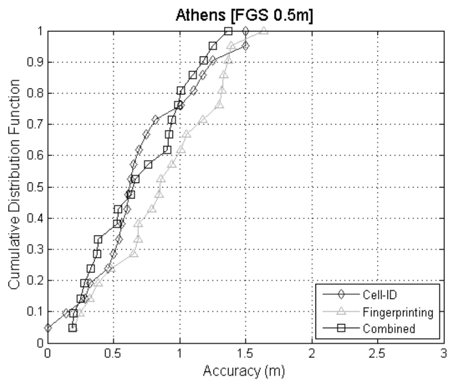
The following parameters were calculated for evaluating the accuracy [10] of the RFID system: a) *Average [in meters (m)]*: the arithmetic mean value of all accuracy metrics for the x and y axis that gives a straightforward value for the accuracy performance; b) *Median (m)*: the value of accuracy below which 50% of observations fall for the x and y axis; c) *67th percentile (m)*: the value of accuracy below which 67% of observations fall for the x and y axis, a performance metric which includes most normal observations and circumstances in general; d) *95th percentile (m)*: the value of accuracy below which 95% of observations fall for the x and y axis, a performance metric which excludes infrequent peaks; and e) *2-d accuracy*: the 2-d accuracy in each case calculated using Pythagoras theorem, namely: $d = \sqrt{(x_{est} - x_{real})^2 + (y_{est} - y_{real})^2}$, where d denotes the 2-d accuracy and $x_{est}, y_{est}, x_{real}, y_{real}$ denote the estimated and real values of positioning coordinates respectively.

4.2 Evaluation results

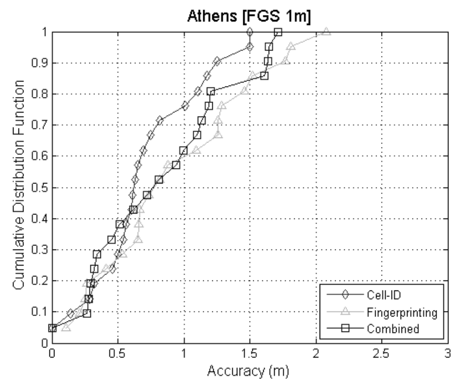
The evaluation results are presented on Table 1 and Figures 7a, b, c, and d. By comparing the fingerprinting algorithm results from the two testbeds we verify that: a) the error decreases as the density of the fingerprints' grid increases, so the FGS of 0.5m is better than 1m; and b) as the system's coverage area increases (cell distance greater) the distance error becomes also greater, so the performance of Athens ($21m^2$) is better than that obtained at Bilbao ($30m^2$). Based on the CDF comparison (Figures 7a to 7d) we can see that the advanced Cell-ID outperforms all algorithms. Also the combined algorithm results in improved performance compared to the performance of the simple fingerprinting but remains inferior to the performance of the Cell-ID algorithm. Further investigation into the combined algorithm fusion logic is required to better quantify its behavior vis-à-vis that of the fingerprint and Cell-ID algorithms.

Table 1. Localization error of advanced Cell-ID, Fingerprinting and Combined algorithms for Athens and Bilbao installations

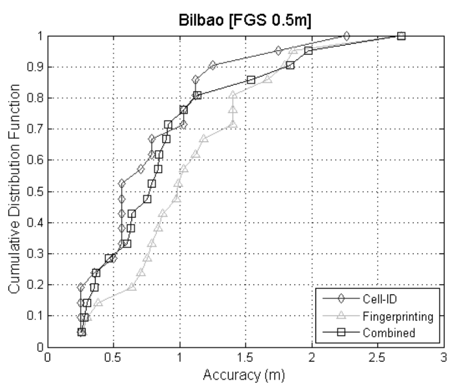
Evaluation	***Athens***	***FGS***	***0.5 m***	***Athens***	***FGS***	***1.0 m***	***Bilbao***	***FGS***	***0.5 m***	***Bilbao***	***FGS***	***1.0 m***
Parameters	Cell-ID	Fingerprint	Combined	Cell-ID	Fingerprint	Combined	Cell-ID	Fingerprint	Combined	Cell-ID	Fingerprint	Combined
Average	0,720	0,889	0,705	0,720	0,939	0,847	0,786	1,098	0,911	0,786	1,235	0,863
Median	0,632	0,856	0,666	0,632	0,817	0,812	0,559	0,993	0,791	0,559	1,222	0,792
67th percent.	0,752	1,052	0,921	0,752	1,257	1,099	0,791	1,184	0,899	0,791	1,615	0,882
95th percent.	1,500	1,386	1,253	1,500	1,810	1,641	1,750	1,857	1,974	1,750	2,236	1,718



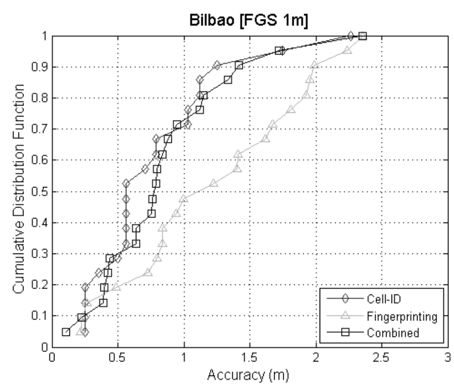
(a)



(b)



(c)



(d)

Figures 7a, b, c, and d. Comparison of localization algorithms in terms of accuracy.

5. CONCLUSIONS

In this paper we presented a cost-effective solution for object localization using passive RFID tags and a single reader with nine multiplexed antennas. The experimental evaluation results from two separate testbeds in Athens, Greece and Bilbao, Spain indicate that sufficient accuracy for localizing even small objects, such as medication packages, can be achieved with the proposed configuration. Due to the special requirement of passive tags for high ERP through panel antennas (with cardioid lobes), experimental results indicate that the tested Cell-ID algorithm provides the highest accuracy amongst all three tested algorithms, namely Cell-ID, Fingerprinting, and Combined method, thus providing a more accurate solution compared to fingerprinting or propagation loss based algorithms.

ACKNOWLEDGMENTS

This work is supported by (a) "DITSEF" (DITSEF-FP7-ICT-SEC-2007-1-225404); "HMFM" (HMFM-FP7-AAL-2008-1/ET: 13591-07/07/2009); and "TASS" (TASS-FP7-SEC-2010-241905) research projects funded by the European Commission and, in part, by the General Secretariat of Research and Technology (GSRT) of the Ministry of Education, Greece; (b) a Ph.D. Fellowship of NCSR "Demokritos" and the Hellenic Ministry of Education; and (c) a Post-Doctoral Fellowship of NCSR "Demokritos" and the Hellenic Ministry of Education.

The authors would like to acknowledge the Tecnalia (Health and Quality of Life Unit) and its research staff for the use of its HomeLab facilities as testbed and demonstrator of the Passive RFID localization system in the context of the HMFM project, and the permission to use the floor layout of the HomeLab shown in Fig 5b.

REFERENCES

[1] Nelson, G. J., [Context-Aware and Location Systems], PhD dissertation, University of Cambridge, 2-3 (1998).
[2] Want, R., "The magic of RFID," ACM Queue 2 (7), New York, 40-48 (2004).
[3] Santos, B. L. D., Smith, L. S., "RFID in the supply chain: panacea or Pandora's box?," Commun. ACM 51 (10), 127-131 (2008).
[4] Chow, H. K. H., Choy, K. L., Lee, W. B., Lau, K. C., "Design of a RFID case-based resource management system for warehouse operations," Expert Systems with Application 30 (2), 561–576 (2006).
[5] Boss, R. W., "RFID technology for libraries," Library Technology Reports, American Library Association, Chicago, (2007).
[6] Ku, W. S., Sakai, K., Sun, M. T., "The Optimal k-Covering Tag Deployment for RFID-Based Localization," JNCA, Special Issue of Journal of Network and Computer Application on RFID Technology, Systems, and Applications, 2-4 (2010).
[7] K., Krishnamurthy, P., "Modeling of Indoor Positioning Systems Based on Location Fingerprinting", Proc. IEEE INFOCOM, (2004).
[8] Mitilineos, S. A., Goufas, J. N., Segou, O. E., and Thomopoulos, S. C. A., "WAX-ROOM: An Indoor WSN-based Localization Platform", Proc. SPIE 7697, 76970X (2010).
[9] Tecnalia, Health and Quality of Life Unit, http://www.tecnalia.info/sect_salud_calidad.php?lang=en&PHPSESSID=kv1bf2a4s94m11s7vk0rrqbp41
[10] Mitilineos, S. A., Kyriazanos, D. M., Segou, O. E., Goufas, J. N. and Thomopoulos, S. C. A., " Indoor Localization with Wireless Sensors Networks", Progress In Electromagnetics Research (PIER) Journal (109), 441–474 (2010).