# Extension of RFID Based Indoor Localization Systems With Smart Tags

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***Abstract*—The indoor localization problem is a method of identifying and finding position (co-ordinates) of requested objects in a well defined area of interest (AoI) in buildings. Beside identification, localization is an important task in several complex industrial environments. Assigning unique Radio Frequency IDentifier (RFID) tags to the objects both the identification and the localization problem can be solved.**

**In this paper, RFID based indoor localization systems, methods, and protocols are analysed. A novel Smart Tag platform called Blackforest with integrated self localization capabilities is introduced. This device can be in either transmitter or receiver role to ensure fast prototyping of localization environments. Higher temporal positioning possibilities and sensor fusion techniques are introduced using the BlackForest nodes. The radio-frequency (RF) characteristcs of the device were analyzed and a localization system was built using Blackforrest nodes. The localization architecture, methods and system configurations are described. After calibration, the suitable accuracy of RFID indoor localization using BlackForest Smart Tags is proven in an indoor office scenario.**

**A hierarchical localization protocol stack is introduced in order to extend existing indoor RFID localization systems using intelligent and co-operative antenna systems with novel Smart-Tags.**

***Index Terms*—Indoor localization, Self Localization, Smart Tag, RFID**

## I. INTRODUCTION

Radio Frequency IDentification (RFID) is an advanced and emerging technology to identify objects based on radio frequency signal transmission and/or reception. Therefore, RFID systems are frequently used to help information systems manage objects in difficult and/or large environments. Besides identification of the tagged object, determining the location is one of the most important and also the most challenging tasks. RFID systems typically consist of readers with antennas and RFID transponders. The reader-antenna pairs and the tags can be fixed (deployed) or mobile. We are focusing on systems that have an infrastructure consisting of fixed reader-antenna pairs and mobile tags on the objects that need to be localized. Mobile readers are not excluded from the system, but are not necessarily parts of the infrastructure. In our research, three types of system architectures can be distinguished, namely Smart Reader Network (SRN), Smart Tag (ST) and Hybrid architectures.

The SRN architecture consists of intelligent reader-antenna pairs connected to a network or a computer server and inexpensive (e.g. passive UHF RFID) tags. In this system architecture, localization is made by the intelligent infrastructure (ambient intelligence) and location information is generated on the infrastructure side. In the ST system, intelligent, active RFID tags are used with (almost) traditional reader-antenna pairs. In this case, self-localization has to be done by the tag and the (self) location information is generated on the tag side. In the hybrid solution, concept SRN and ST are combined.

In conclusion, the article details our practical results in RFID based localization solutions. The prototype of a new generation of Smart Transponder is described in Section III, that is capable of self-localization based on information obtained from RFID antennas. Our ideas on hybrid applications and the combination of RFID systems with other technologies are also detailed. The self-localizing transponder and theconnected middleware resting on mathematical foundations can be used with significantly greater precision for indoor localization than current devices.

In the following section, we analyse the RFID based localization methods, systems and our previous works in Section II. Introducing the novel self localization concept is followed by the description of hardware prototype of Smart Tag called BlackForest and localization methods in Section III. The results and measurements are demonstrated in office environments in Section IV.

Localization methods are based on principles, models, measurements, and evaluation methods. A principle is a plan that determines what parameters to model, measure, and evaluate. [1][2] In case of multilateration (or trilateration) we have to determine distances using measurements and models, thus the position can be estimated from the best candidates for intersection of spheres or circles. In case of triangulation we have to determine angles and estimate position using the best candidates for intersection of directions given by the angles. We can also calculate position from distance differences using the best candidates for intersection of paraboloids.

Modelling is an important part of a localization system. Based on the principle, the environment and the given hardware devices we can assume different types of antenna models,

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The RFID research project was supported by the European Union and the State of Hungary, co-financed by the European Social Fund in the framework of TÁMOP-4.2.2.C-11/1/KONV-2012-0014.

propagation models, kinematic models, and error models that can be used to refine measurements and create perception from the measured data. The result of the measurement is the input of our models; thus, the measured parameters must be determined using the models and the selected principle.

Using triangulation we can measure the phase difference of arrival (PoA), angle of arrival[1] (AoA), or the angle of departure[2] (AoD). Using multilateration we can measure the time of arrival[3] (ToA) or the received signal strength (RSS). In the case of distance difference, we can measure the time difference of arrival[4](TDoA).

Evaluation is typically an optimisation using the measured data and given models. Fingerprinting is a widely used method for evaluation that means we have to measure signal parameters offline at different locations. Using the measured signal parameters we can infer to the best candidate from (or between) the recorded points.

## II. Related works

The ”You are here” (YAH) map is a basic type of localization system. Using acoustic, visual, or radio-frequency (RF) landmarks one can determine its location close to the landmark. It can be used by humans or machines. The landmarks can be QR codes or - in our case - NFC tags for instance. Fingerprinting based on a received signal strength indicator (RSSI) is often used for RFID localization [3] together with different types of classification and machine learning methods [4][5].

Models based on RSSI and Probabilistic Localization Algorithm (PLA) are also used together [6]. Propagation and path loss are modelled, and using the probabilistic distribution of the RSSI, location can be estimated by a Bayesian localization scheme. Data analysis methods like multidimensional scaling (MDS) can be used to locate active RFID tags based on RSS measurements [7]. Phase difference (PoA) estimation using multiple antennas is often used to locate RFID tags [8][9]. PoA can be augmented with other methods. At the reader side, reference tags and different reader output power setting strategies can be used to locate a tag. [10][11]

RFID tags can be modified or extended with other technologies to achieve the best results. Hybrid systems use acoustic [12], visual [13][14], or inertial sensor data [15]. Simultaneous Localization and Mapping (SLAM) methods can be used to determine the location of mobile readers and RFID tags. Typically, additional geometric information is needed [16]. A modified tag called ”sense-a-tag” can measure backscattering in the near field and save this kind of location information [17]. Using an RFID reader and normal RFID tags placed on known locations, the system can track ”sense-a-tags” attached to the objects.

In our previous work, a novel antenna design and a localization concept were defined [19]. The novel device was called an “Nodding antenna”, that can change its characteristics and ”look” to 6 directions in space with different output power. Using this, the RFID localization can be extended beyond the area covered by the RFID reader system. The novel concept called Location on Tag (LoT) is a Smart Reader Network (SRN) based localization protocol that uses the limited memory of the passive RFID transponder to store location information. The Smart Readers can determine the position of the tag and then write this current position into a circular list defined in the tag memory. The path of the tags which are travelling with this information can be reconstructed by other Smart Readers. A mathematical framework was developed to recover the possible path of moving RFID transponders in indoor environments [20][21]. This framework is suitable in cases when the tag becomes unreadable or enters into an uncovered area.

## III. Self localization methods and the hardware prototype

The Smart Tag (ST) RFID localization architecture is the inside out version of the SRN solution. In this case, tag self-localization is done onboard using an almost typical reader infrastructure to estimate the own position of the tag in a reference coordinate system.

The components of this ST system can be seen in Figure 1. The system consists of multiple readers/transmitters with known positions and IDs. These reader parameters should be transmitted to the Smart Tag. Using distance and/or angle estimations, Smart Tag can determine its position (using trilateration, triangulation or probability based methods). In the following sections we describe the requirements of components, measurements, methods, and the hardware/software components of the Smart Tag localization system architecture.

To calculate the position the Smart Tag has to measure distances or angles. We decided to measure the signal strength indicator (RSSI) of the readers in real time. This can lead to distance estimation or angle calculation (in the case of object rotating). The reader-antenna pairs have to be distinguished; therefore, the reader-antennas are broadcasting unique ID-s. Methods require the coordinates of the antennas for position estimation; thus, the antenna ID-Coordinate pairs should be transmitted to the tag memory. Smart Tags have to execute complex algorithms onboard, thus one needs enough memory and computational capacity. Active (or semipassive) ones have to be used, since an external power supply of the tag is needed.

The input signal for RSS based localization is suffering from artifacts caused by filtering that is typically made by the consumer RF receiver circuit/device to filter out dynamic changes to produce more stable (and repeatable) RSS values. A method that uses propagation models can take advantage of the low level (raw) RSS signal but cannot deal with a signal that is filtered and has low temporal resolution. Moreover, we

[1]Angle of arrival (AoA) measurement is a method for determining the direction of propagation of a radio-frequency wave incident on an antenna array. AoA determines the direction by measuring the Time Difference of Arrival (TDoA) at individual elements of the array.

[2]Angle of Departure measurement is done when the transmitter transmits through multiple antennas and the receiver resolves the angle of signal departure based on the received signals.

[3]ToA the travel time of a radio signal from a single transmitter to a remote single receiver.

[4]TDoA is the time differences between received signals measured with multiple antennas. Each measurement defines a hyperboloid of possible locations of the transmitter.

designed a universal device to measure RSS values directly in our experiments. The device called BlackForest can monitor RF channels from an SMA[5] antenna connector in real time from 100MHz to 1GHz with 1Hz resolution and mix it down to a 200-40000Hz baseband. The I and Q signal can be processed by analog-digital converters (ADs) of an audio card since I and Q signals are available on a 3.5mm stereo audio jack connector. The received sensitivity is adjustable from 0 to 60 dB and the modulation method is also selectable from the list of ASK[6], OOK[7], BPSK[8], FM[9] and FSK[10]. For further experiments and localization method evaluation, the BlackForest device has a 3D gyroscope and an accelerometer.

To have a complete system, BlackForest can also transmit (Rx and Tx adjustable with jumper), and the transmission frequency is also adjustable. The panel is supplied by external 5V, the other components are supplied via LDO[11] modules with 3.3V and 2.4V regulated outputs.

The transmission and the received functionality make BlackForest a universal platform to evaluate experimental localization methods without a large amount of deployable, fixed RFID reader-antenna pairs. Furthermore, it is possible to analyse different situations, system configurations, and scales. In a current setup, the readers are BlackForest-Tx nodes and the node that is being localized is a BlackForest-Rx node and it is connected to a sound card in a PC. The transmission frequency is in the 868 MHz band, the frequency of channel n is $868MHz + n * 1KHz$. We identify reader nodes using frequency division multiplexing (FDM), which means that each reader transmits signals at different frequencies. The received signal strength at a given reader frequency means a distance candidate with error factors such as path attenuation. Localization methods can take into account these error factors using propagation models and/or mapping. Using the BlackForest hardware, our goal is to analyze the applicability of different propagation models for RFID localization solutions in different environments.

The arrangement of the infrastructure is also an important part of our research, therefore we were considering different optimization methods to find optimal positions of the readers (beacons) in a given environment. To ensure a higher spatial and temporal quality of RFID localization, transponders have to be extended with sensors that can measure relative displacement and rotation of the tag between RF localization measurements or in areas that are not covered by readers.

[5]SMA (SubMiniature version A) connectors are semi-precision coaxial RF connectors.

[6]Amplitude-Shift Keying is a form of amplitude modulation that represents digital data as variations in the amplitude of a carrier wave.

[7]On-Off Keying denotes the simplest form of Amplitude-Shift Keying (ASK) modulation that represents digital data at the presence or absence of a carrier wave.

[8]Binary Phase-Shift Keying is the simplest variant of Phase-Shift Keying and conveys data by switching the phase of a reference signal.

[9]Frequency Modulation is the encoding of information in a carrier wave by varying the instantaneous frequency of the wave.

[10]Frequency-Shift Keying is a frequency modulation scheme in which digital information is transmitted through discrete frequency changes of a carrier signal

[11]A low-dropout or LDO regulator is a DC linear voltage regulator that can regulate the output voltage even when the supply voltage is very close to the output voltage.

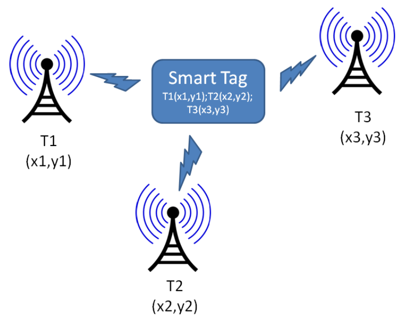


Fig. 1. BlackForest Smart Tag localization arrangement

Inertial sensors like the accelerometer and gyroscope can help to increase the temporal resolution of the localization. Therefore, we designed BlackForest to be able to measure 3 axes of acceleration and angular velocity using an accelerometer and a gyroscope IC. After choosing the sensors, we considered high level sensor fusion methods to increase the quality of the RF localization using the inertial measurements.

The basic BlackForest positioning system (Figure 1) consists of at least 3 BlackForest as transmitters: $T1, T2, T3$ and at least one BlackForest Smart Tag as an active receiver: $SmartTag$. The transmitters $T1, T2, T3$ are configured as RFID transmitters (Tx nodes) and the receiver $SmartTag$ is configured as a receiver node (Rx node). Transmitters are arranged in a nodes of a triangle on a plane, thus, the positioning area is the area covered by at least 3 transmitters. This can be seen in Figure 2.

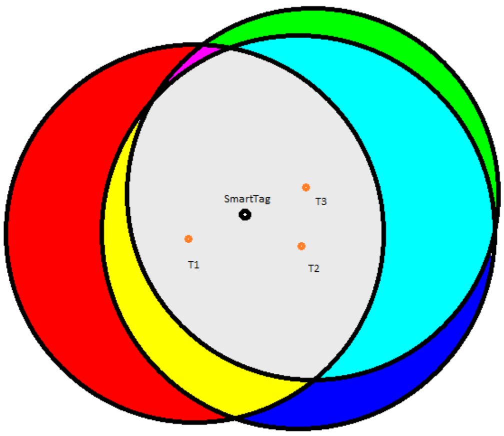


Fig. 2. BlackForest transmitter coverages

To locate the BlackForest SmartTag, we use a log distance path loss model (LDPL). This expresses a relationship between the received signal strength (RSS) and the distance from the transmitter [22].

$$P_{rx} = P_{tx} - P_{ref} - 10\alpha \log d - X\sigma \quad (1)$$

Here, $P_{rx}$ is the power of received signal (RSS), $P_{tx}$ is the transmitter output power, $P_{ref}$ is the received signal power at the reference distance $(1m)$, $d$ is the unknown distance from the transmitter to the receiver node, $\alpha$ is an exponential model parameter and $X$ is the term for further attenuation. The measurements can be done in multiple coordinates at different distances from the transmitters.

From these measurements, the model parameters ($\alpha$,$X$) can be estimated by using a nonlinear fitting method. In this case, the Levenberg–Marquardt algorithm[12] was chosen to calculate the parameters of the LDPL models. Transmitters can broadcast their positions, IDs and the calibrated attenuation parameters, thus, these parameters are downloaded to the tag.

For a transmitter, the distance can be estimated using the following formula:

$$d = 10^{\frac{-P_{rx}-P_{offset}}{10\alpha}} \tag{2}$$

where $P_{offset} = P_{tx} - P_{ref}$.

Once LDPL models are calibrated properly, the transmitter can estimate the position by building a possibility map from the measured values and transmitter coordinates and LDPL parameters.

The transmitters are communicating their IDs ($Ti$), coordinates($xi, yi$) and model parameters ($Pi$), therefore, when the $SmartTag$ arrives into the positioning area it registers these values into its memory:

$$\begin{aligned} D =&\{(T1, P1, x1, y1),\\ &(T2, P2, x2, y2), (T3, P3, x3, y3)\} \end{aligned} \tag{3}$$

BlackForest receiver node $SmartTag$ measures RSS values for each visible $Ti$ transmitters and registers them with the transmitter coordinates as measurements:

$$\begin{aligned} M =&\{(M1, P1, x1, y1),\\ &(M2, P2, x2, y2), (M3, P3, x3, y3)\} \end{aligned} \tag{4}$$

Possibility map onboard estimation is a hard task for embedded systems, therefore, the calculation is done in an equidistant grid of $NxM$ points over the positioning area. Possibilities from an individual distance measurement based on the LDPL model is represented as a Gaussian along a circle with the empiricaly set $\sigma = 2.5m$ parameter. The maximum possibility value can be chosen as $SmartTag$ position candidate.

The transmitters are broadcasting multiple LDPL model parameters depending on the context. This is formed in the attenuation parameter $X$. Typically, the parameters can be determined for each rooms in the building to model the attenuation of the walls between the transmitter and the SmartTag node. Since the tag can test multiple configurations of the model parameters (depending on the room) for a measurement set , the best candidate with the highest possibility can be chosen.

Previous position and inertial sensor measurements over time was used both as selectors for Area of Interest (AoI) and by filtering the current probablity map. A 2D Gaussian filter[13] with $\sigma = 2m$ was chosen and was used at the point that was estimated from of the previous locations and intertial sensor measurements using an Extended Kalman Filter (EKF)[14] [23].

An extended version of the BlackForest node (EBF) was developed with a 2D linear square array of 4 antennas. The array is capable of Angle of Arrival (AoA) measurements. The estimation of the angles was done using the ESPRIT method [24][25]. Alternatively, the position with lower accuracy can be calculated from these directions only, using the non-linear optimization proposed in [26]. Although we used the directions from the AoA measurements to futher filter the probability map using multiple one-dimensional Gaussian filters with the empirically set $\sigma = 1.5m$ parameter along the given direction.

The novel tag can be used in the previously developed RFID localization system: Location on Tag (LoT) concept [19] was easily adapted to the system since the location is determined at the tag side.

To enhance the possibility of finding the location of the tag, all of the methods can be integrated in one system. Smart Tag can determine and store its location and this data can be sent to the readers. In this case, the reader can determine the validity of the location of the Smart Tag. If it fails, the following methods are performed.

In case of the Smart Reader localization method using LoT [19], the locations (path) are in the tag memory. Smart Readers execute the defined LoT algorithms to determine the path of the tag if the tag is in the covered area. If it is known that the tag is in the area but it cannot be read for a while (e.g. because it is temporarily in an uncovered area), its position can still be estimated using the mathematical framework (see in [20], [21]). Using these three methods, location can be determined or estimated in all cases and by a discrete time. This combination of localization methods is suitable for various indoor and outdoor localization tasks.

## IV. RESULTS

BlackForrest receiver node measures RSS values utilizing $868MHz$ frequency and $-15dBm$ output power at the transmitter node. An Anritsu MT8222A BTS Master device was placed at different distances from the transmitter node. The results can be seen in Figure 4.

On the second floor of a typical office building (including walls) a room measuring 40m x 30m was chosen as the localization area. Positioning measurements using the LDPL model was started with the model calibration process (Figure 3). We measured RSS for different distances from the transmitter and fitted a model using the Levenberg–Marquardt algorithm (LMA).

We used 3 BlackForest nodes as transmitters and one BlackForest SmartTag receiver node at the position $X = 138$ and $Y = 170$. This arrangement is shown in Figure 5.

The framework can calculate the possibility of the tag position in a co-ordinate. This can be visualized for a set of measurement as a probability map. A calculated possibility map is shown in Figure 6. The maximum possibility is at the

[12]The Levenberg–Marquardt algorithm is used to solve non-linear least squares problems. These minimization problems arise especially in least squares curve fitting.

[13]Gaussian filter is a filter whose impulse response is a Gaussian function (or an approximation to it).

[14]Kalman filtering is an algorithm that uses a series of measurements observed over time, containing statistical noise and other inaccuracies, and produces estimates of unknown variables.

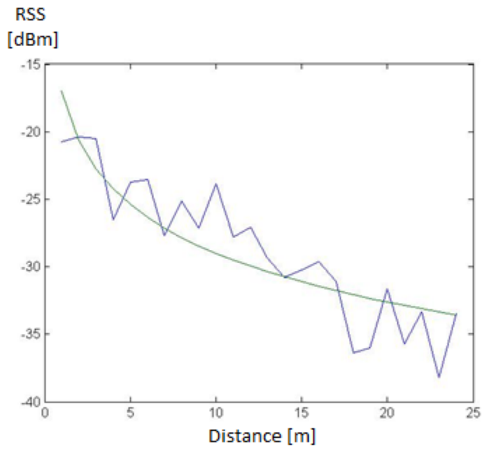


Fig. 3. Measured RSS values at different distances (blue) used for calibration and the fitted model (green)

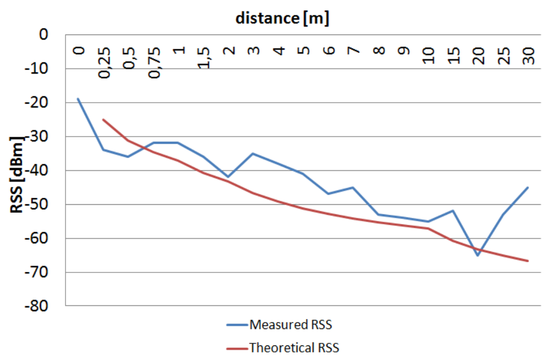


Fig. 4. Measured and theoretical RSS values

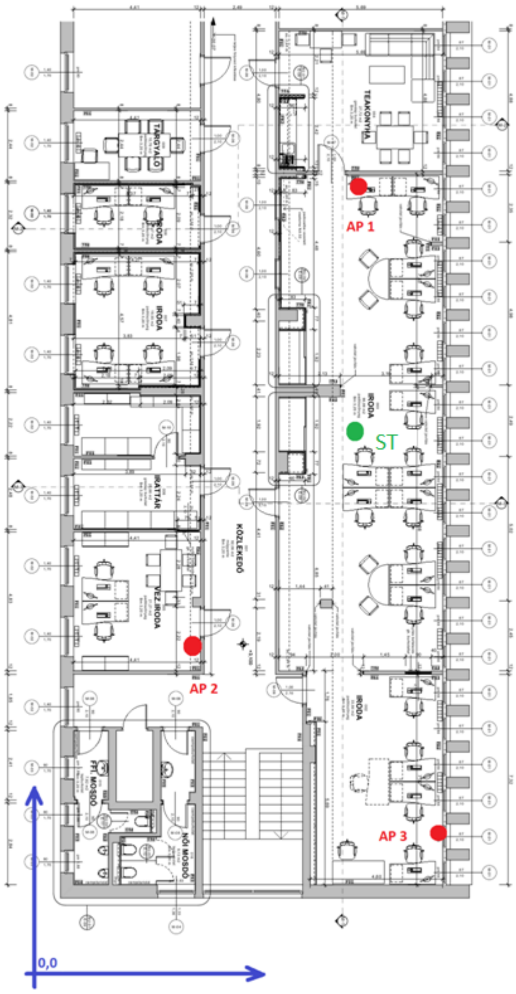


Fig. 5. System arrangement: reference coordinate system (blue), Smart Tag (green), transmitter nodes (red)

coordinates $X = 116$ and $Y = 144$. For this measurement, RSS based the localization error is $3,41m$.

After the previous location based and DoA filtering process, estimation ended in $X = 130$ and $Y = 166$, thus, the overall localization error is $0.89m$. These results can be seen in Figure 7 and 8.

After single measurements, multiple measurements were done and also multiple nodes were placed in the positioning area. We measured 20 samples at different locations. We used 2, 5 and 10 receiver nodes to analyze the effect of the multinode environment to the positioning accuracy. We found that the accuracy did not suffer of additional errors due to the increase of the number of the SmartTags. The average results can be seen on Table I.

TABLE I
POSITIONING ERROR IN MULTINODE ENVIRONMENT

| Number of SmartTags | Average positioning error |
|---|---|
| 1 | 0.92m |
| 2 | 0.76m |
| 5 | 0.87m |
| 10 | 0.94m |

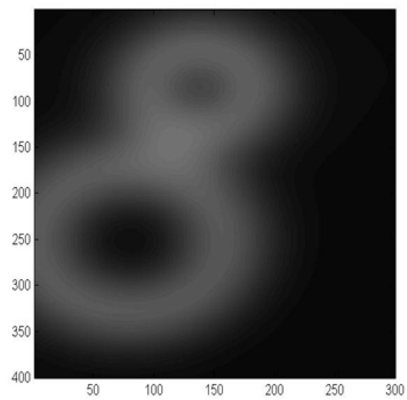


Fig. 6. Possibility map in the resolution of 10 cm

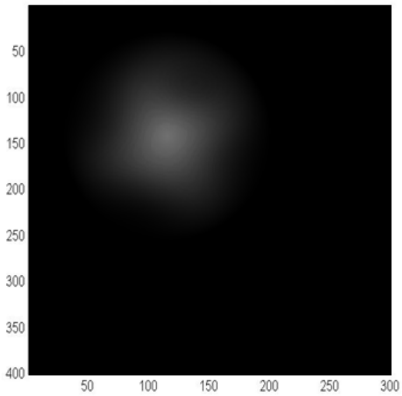


Fig. 7. Possibility map filtered by the previous location information in the resolution of 10 cm

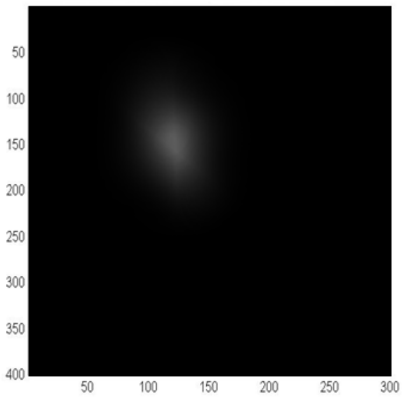


Fig. 8. Possibility map filtered by the previous location information and DoA, in the resolution of 10 cm

Table II summarizes our results compared to some of the recent and available RFID based positioning solutions.

TABLE II
POSITIONING ERROR COMPARISON

| System | Average positioning error |
|---|---|
| VLSL and LANDMARC[27] | 2.1m |
| BlackFIR[28] | 1.0m |
| Our method | 0.8m |

However, our method requires calibration of the used models and uses signal processing at the tag side, it does not require complex antennas at the system side, thus, the infrastructure is cost effective.

## V. CONCLUSION

After discussing systems and methods for RFID based indoor positioning, a novel SmartTag platform called Blackforest and an improved version called EBF were introduced. Later is capable of measuring RSS, Angle of Arrival (AoA) and inertial motion parameters. A novel method based on the system of EBF SmartTags and multiple transmitters was presented for self localization. The method uses RSS based adaptive LDPL models and Kalman filtering for position estimation and AoA measurements for position refinement. The novel device platform and localization method was tested in indoor office scenario and it was found as a solution in terms of mean positioning error against other available methods. Moreover, the system can efficiently extend previous localization architectures.

To enhance the possibility of finding the location of the tag, the self-localization, the Location-on-Tag method and the mathematical framework can be integrated in one system as a hierarchical localization architecture. This combination of localization methods is suitable for various indoor and outdoor localization tasks.

As a future research project, we would like to design and analyse a new, smaller version of the SmartTag prototype and introduce enhanced adaptive distance models and localization methods to the indoor positioning platform.

## ACKNOWLEDGMENT

The authors would like to thank to the members of BAY-IKTI, namely Márton Törőcsik, Emil Tóth, Péter Pók, Gábor Kis-Vámosi, Ádám Ács and the members of Institute of Mathematics and Informatics, EKE.

The authors and institutes also would like to thank the support of European Union and the State of Hungary, and the European Social Fund.

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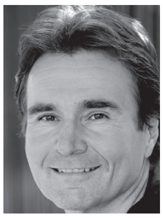

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