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Mixed-Mode Wireless Indoor Positioning System Using Proximity Detection and Database Correlation

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***Abstract*—The paper presents a prototype mixed-mode wireless indoor positioning and navigation system. The main goal of the system is to provide accurate and reliable location information for visually impaired users. The system also enables access to location related context information. The radio nodes of the network can operate in two power modes providing basis for both rough and precise user positioning. The paper describes an overview of the system architecture and the user interface suited to the needs of the visually impaired. Then, the details of the implemented positioning methods are presented. Finally, the results of experimental evaluation of positioning accuracy obtained using different classification strategies are discussed.**

***Index Terms*—Context-aware services, indoor radio communication, location services, personal communication networks, pervasive computing, radio navigation, wireless sensor networks**

I. Introduction

Recently, a number of wireless indoor positioning systems have been developed and numerous research works are reported in the literature. One of the first indoor positioning systems that used radio beacons and Received Signal Strength Indicator (RSSI) measurements was the RADAR system developed by Microsoft Research [1]. From that time the problem of indoor positioning and navigation has been widely addressed around the world [2-14]. Hence maintaining low deployment and maintenance costs is among the most important objectives of the research, majority of the solutions reported in the literature rely on radio signal strength measurements [23-32].

Received signal strength (RSS) measurements can be incorporated to location services in several ways. First of all, radio wave indoor propagation models can be used to determine the possible location of the terminal. This approach requires detailed description of the propagation environment and thus is difficult to implement. Another approach involves the use of database search methods to calculate user terminal position. Therefore, it is necessary to provide reference RSSI measurements (i.e. measurements taken in predefined locations) that are stored in the reference database, and which are then used by location estimation algorithms.

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One of the application areas of indoor positioning systems is aiding the visually impaired and blind in navigation [22] and orientation and thus in their everyday activities. Almost all electronic travel aids (ETA) for the visually impaired [15-20] require accurate information on current user location. Obtaining precise information on user location can for example facilitate access to public services offered in large buildings (e.g. city halls, hospitals) by aiding to locate rooms or by giving a remote guidance on how to reach the destination. Contemporary satellite navigation systems like GPS provide positioning services sufficient for successful navigation in outdoor scenarios. However, the use of satellite positioning systems is usually impossible in indoor and densely built-up urban areas only. Thus, most of ETAs offered on the market make use of local networks of reference stations that transmit infrared [15] or radio signals [16-18]. The transmitters are used to identify various points of interest (POI) like bus stops, entrances to public buildings, etc.

In the paper, we present a mixed-mode RSSI-based wireless positioning system developed as a part of a complex solution aiding the visually impaired in indoor navigation. The remainder of the paper is organized as follows. Section II presents an overview of the positioning system architecture. Section III provides details of the proposed positioning approach, while Section IV gives details of the user interface module dedicated for visually impaired users. Section V describes experiments conducted to evaluate the performance of the system, while Section VI discusses the results of these experiments. Section VII summarizes our work.

II. System Architecture

The general architecture of the proposed indoor positioning system consists of a local localization server, a local database server and an optional global localization server, as previously described in [21]. A wide range of portable user devices (smartphones, notebooks, tablets etc.) may be used as system terminals, however the terminals should have the capability to measure strength of the signals transmitted by system reference stations mounted inside a building. Thus, a dedicated software or hardware is necessary to read the measurement data and pass the results to the local positioning server.

The key tasks of the local positioning server include

- storing information about the layout of the area (a digital map) it serves (e.g. of an office building);

- making use of the local database engine to store reference measurement data;
- computing the probable user location based on the RSSI measurement values reported by the terminal;
- management of communication with the global localization server, if available.

The general architecture of the proposed system is shown in Fig. 1. All the components of the system communicate and exchange data using XML/JSON and SOAP-based Web Services.

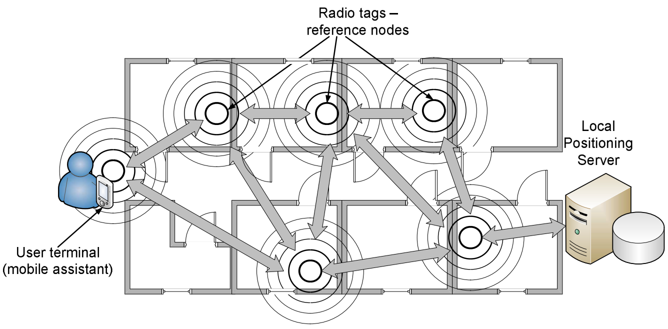


Fig. 1. General architecture of the indoor positioning system.

III. POSITIONING TECHNIQUES

A variety of techniques can be employed to estimate the position of a wireless network terminal. Majority of systems described in the literature base on measurements of signal parameters transmitted by system reference stations. Then, the distances of the terminal to at least some of the reference nodes can be calculated and the approximate position of the terminal can be estimated. Among the most commonly used signal properties are propagation time, angle of arrival, and signal strength, however due to low deployment and maintenance costs, majority of the solutions reported in the literature rely on received signal strength measurements [2, 23-32].

The most straightforward method to estimate the position of a radio terminal is to determine whether it is within the coverage of some reference station. The accuracy of positioning with this approach strongly depends on the range of reference transmitters. However, when reference stations transmit signals with relatively low power, the position of the user terminal may be well approximated by the known location of the reference transmitter. This approach is called *proximity detection*. Practical implementation of this positioning technique involves installation of many reference nodes, often called *radio tags*. However, due to simple tag's construction the overall system installation cost might remain low. This technique offers good accuracy, however it strongly depends on the number of installed reference tags. The idea of positioning system using proximity detection is shown in Fig. 2.

As previously mentioned, distance estimation techniques involving radio wave propagation modeling are widely used in positioning systems. However, due very high complexity of indoor radio wave propagation environment, applicability of these methods is limited to outdoor areas. In typical indoor scenarios, strong multipath propagation effects make it impossible to unambiguously relate measured signal parameter value to a distance from the transmitter. Even along short propagation paths, signal parameters may exhibit very strong variability. Another factor limiting performance of positioning methods is time variability of indoor radio channel characteristics. For example, depending of the time of the day, the offices may either be crowded or almost empty what may result in significant changes of the reported values.

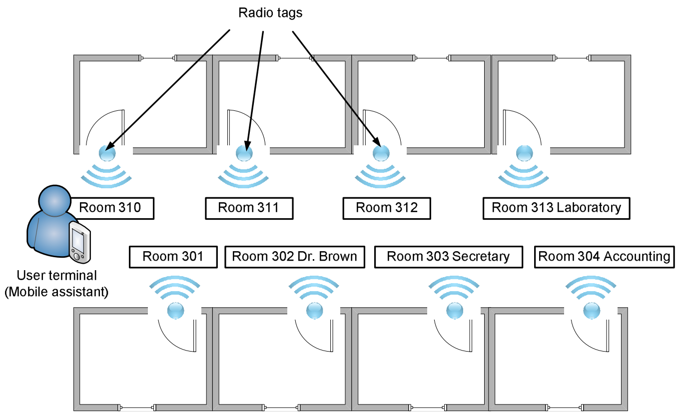


Fig. 2. Proximity detection – presentation of indoor location of the terminal and position related context information (room number).

Therefore, there is a need to search for new positioning methods for indoor applications. One of the approaches that is adequate for indoor systems assumes the use of correlation analysis of reported signal parameter values with some reference data recorded at predefined locations. As database search methods (Fig. 3) rely on evaluation of similarity of measured signal characteristics at actual location to the reference datasets, these methods are not so prone to multipath and shadowing effects as the methods based on radio wave propagation modeling.

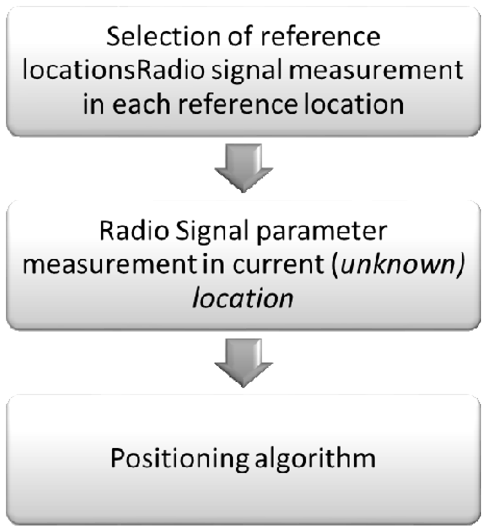


Fig. 3. Block diagram of DCM positioning method

Despite of the fact that database correlation methods may be based on analysis of any available signal parameters, most of practical implementations involve received signal strength measurements. The advantage of the use of RSSI is that most of contemporary radio receivers provide possibility to monitor RSSI level and a wide range of devices can be used with a positioning system without a need to implement any hardware modifications.

The use of database search methods makes it also possible to reduce the influence of RSSI time variability by the use of normalization to the value read from a given reference signal source.

A. *Proposed Positioning Technique*

The proposed implementation of a wireless indoor positioning system involves received signal strength (RSSI) measurements to estimate terminal position. It makes use of the advantages of both aforementioned approaches, i.e. proximity detection and database search methods.

Hence proximity detection is most effective and accurate when area served by a single reference tag is relatively small, the tags should be equipped with radio transmitters supporting low transmit power modes. On the other hand, database search method accuracy increases with the number of sources of reference signals. In that case, the nodes should be capable to transmit reference signals over relatively large areas. Moreover, the coverage areas of neighboring transmitters should overlap.

It is worth mentioning, that position information in the form of absolute geographical coordinates of the user is not the most expected output from indoor navigation and positioning systems. Geographical coordinates are more suitable for outdoor positioning, mainly due to easy integration with GIS systems.

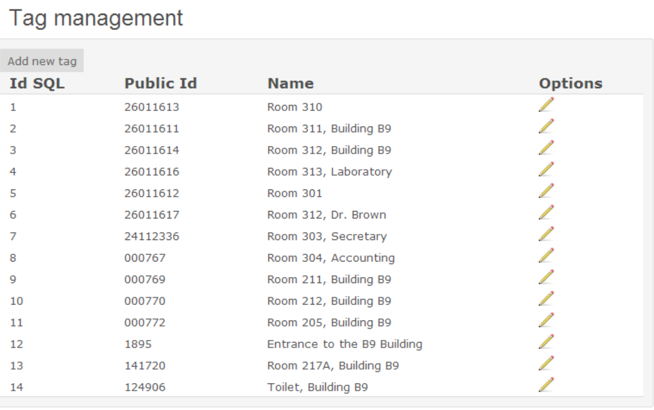
Moreover, in indoor applications accurate and reliable altitude estimation is required. Although in outdoor scenarios the use of absolute altitude above ground or sea level as altitude descriptor is the most convenient, in indoor scenarios floor index should be considered as the natural way of expressing in-building altitude of travelling people.

Therefore, the proposed indoor positioning system makes use of area-based context-related positioning. Area-based positioning systems provide end users with context information related to the current zone of the building. The system output data set includes but is not limited to:

- floor index or name (if applicable),
- zone within a building (e.g. “north wing”),
- room or office number or its name (e.g. “kitchen” or “auditory no. 416”),
- additional site-related information (like name of current lecture in an auditory room).

Web based application for management of context information is presented in Fig. 4.

Moreover, the proposed system returns absolute coordinates of the user terminal to ensure backward compatibility.


Tag management

Add new tag

Id SQL	Public Id	Name	Options
1	26011613	Room 310	
2	26011611	Room 311, Building B9	
3	26011614	Room 312, Building B9	
4	26011616	Room 313, Laboratory	
5	26011612	Room 301	
6	26011617	Room 312, Dr. Brown	
7	24112336	Room 303, Secretary	
8	000767	Room 304, Accounting	
9	000769	Room 211, Building B9	
10	000770	Room 212, Building B9	
11	000772	Room 205, Building B9	
12	1895	Entrance to the B9 Building	
13	141720	Room 217A, Building B9	
14	124906	Toilet, Building B9	

Fig. 4. Web application interface for the management of the radio tags database. Each tag has its unique id and public id (address). Each of the database entries can be edited or deleted.

IV. Positioning Network Interface Module

To enable access to the dedicated positioning network from popular mobile devices (smartphone, tablet, etc.), a dedicated interfacing PilotIE (Fig. 6) device was designed. Proprietary communication protocol with the network of radio beacons enables variable output power settings and provides access to the received signal strength (RSSI) and link quality (LQI) indicators. PilotIE is designed as a device interfacing the radio beacons scattered in the building and the user’s mobile device (via Bluetooth).

Another feature of the PilotIE device is the ability to control selected functions of dedicated mobile applications. Most of the modern smartphones are equipped with a touchscreen and they do not have physical keys. Interaction with a mobile phone requires the use of both hands and may be especially uncomfortable for blind or visually impaired users, who at the same time are often using a white cane. In our solution mobile phone can be hidden in a pocket, which significantly improves the safety of the blind and protect the device in case of falling. Because modern mobile phones are usually equipped with very good quality speech synthesizers, voice messages could be transmitted to the users via the hands-free set. Built-in physical keyboard allows to change systems parameters, like speech speed or volume. It also enables the possibility to re-read the previous message.

Device is built based on the Texas Instruments low-power, 16-bit microcontroller (MSP430F5438A) with the external CC1101 radio transceiver and the TiWi-uB2 Bluetooth 2.1+EDR and BLE 4.0 module. Bluetooth dual mode module can be switched to work in the new, energy efficient Bluetooth 4.0 Low Energy standard (only available in the newest mobile devices) or classic Bluetooth 2.1+EDR mode (most of older devices). It is equipped with two status LEDs and eight user buttons. Device is assembled in a 78mm × 48mm × 20mm enclosure with a single BL-5C (1020 mAh) Li-Ion battery.

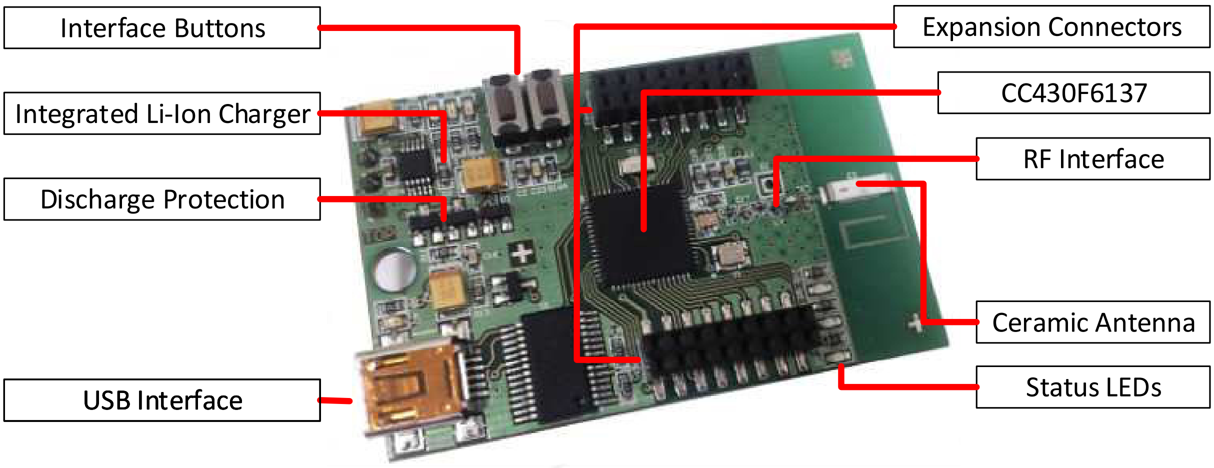


Fig. 5 Radio beacon unit – construction details.

Fig. 6. PilotIE – an interface module for positioning network and mobile phone communications.

V. Experiment Setup

In order to verify the proposed positioning algorithms a number of experiments were undertaken with the use of self-made radio beacons and dedicated user interface module (Fig. 6).

Our prototype radio beacon modules (Fig. 5 and Fig. 7) were built based on the ultralow-power microcontroller system-on-chip (CC430 family, developed by Texas Instruments) with integrated RF transceiver core (CC1101) for the sub-1-GHz industrial, scientific and medical (ISM) radio bands. The CC430F6137 core MCU features 32KB of flash memory, 4KB of RAM, two 16-bit timers, a high-performance 12-bit analog-to-digital converter (ADC), universal serial communication interfaces, a real-time clock module and 44 I/O pins.

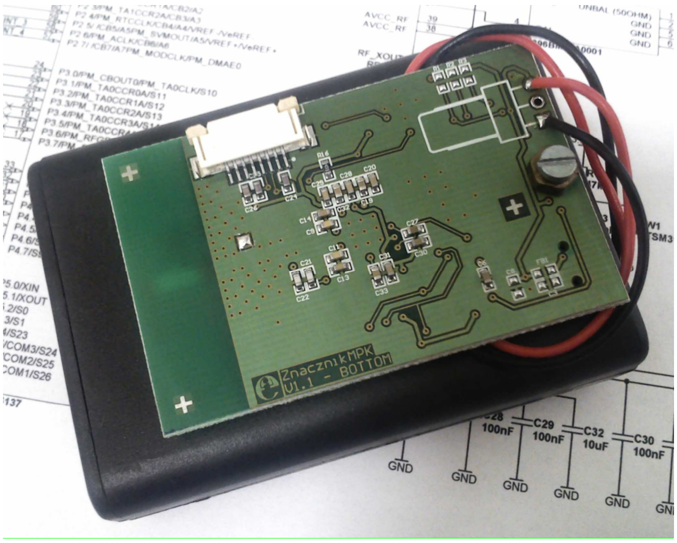


Fig. 7. Radio beacon unit.

Integrated radio module ensures easy implementation of proprietary communication protocols with variable output power settings and provides access to the received signal strength (RSSI) and link quality (LQI) indicators. CC1101 RF transceiver is able to work with programmable data rates ranging from 0.6 to 500 kBaud, programmable output power levels from -30 to +12 dBm, and high sensitivity (up to -117 dBm at 0.6 kBaud for 1% Packet Error Rate).

Radio beacon was optimized to achieve extended battery life. Integrated lithium-ion battery charger and battery discharge protection circuit enables the use of cheap Li-Ion batteries. Device is able to communicate with the PC over the FT232R USB UART interface bridge. Three programmable LEDs and a single TACT switch are provided for status indication and optional configuration. All unused A/D inputs, I2C/SPI buses, GPIOs, and external interrupt inputs are routed out to the expansion connector on top of the module for possible future applications.

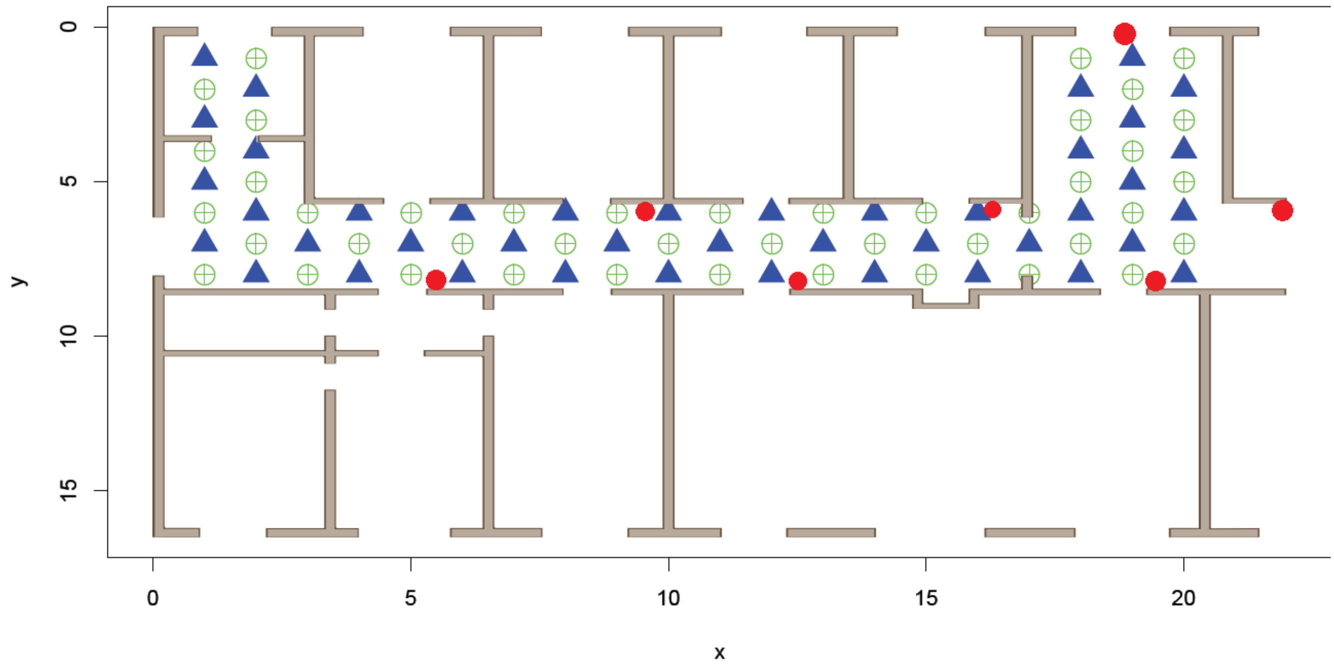


Fig. 8. Experimental setup - RSSI measurement locations (blue - training subset, green - test subset, red - radio beacons)

Device integrates a small ceramic antenna (Johanson Technology 0868AT43A0020, with a peak gain of -1.0 dBi and average gain of -4.0 dBi) or can be used with an optional unipol wire antenna. In the presented application radio beacons are pre-configured for the 868MHz band with the data rate of 38.4 kBaud and 2-GFSK modulation (20 kHz deviation).

Device was designed on a small PCB (55 × 35 mm) which perfectly fits 3xAA battery holder or can be mounted in the KM-27 housing (64.5mm × 46.8mm × 22.3mm) with a single BL-5C (1020mAh) Li-Ion battery.

Each of the fourteen radio beacons used in experiments was equipped with omnidirectional wired antenna. The nodes were distributed across test bed area (seven locations are marked in Fig. 8). All the beacons transmitted packets with two power levels: -30 dBm and -12 dBm. This approach benefits in ability to combine proximity-based methods with database search within a single machine learning algorithm.

Experiment was settled in office building with long and narrow corridor in its central part and number of offices at the sides of that corridor. RSSI measurements were collected in test points arranged in two grids. Fourteen radio beacons were placed in the experiment area. Placement of radio beacons and locations of the measurement points is shown in Fig. 8.

While one dataset was used for training the algorithms, the second one was intended to be used to verify positioning accuracy. Nevertheless, each measurement record contained 10 RSSI readouts taken with the sampling interval of 2.5 seconds.

On the basis of previous research [21] two positioning algorithms were developed. The first one employs Multilayer Perceptron Artificial Neural Network (MLP). The other one was Random Forests (RF) [33]. Moreover, k-Nearest Neighbors (kNN) algorithm with k=7 was used as a reference method. All the algorithms were trained using records from learning dataset and positioning accuracy was verified with separate testing set. We examined and compared positioning accuracy for the following three scenarios:

- Using DCM-only system, i.e. only the subsets of RSSI measurements for packets transmitted with the power of -12 dBm were used.
- Using proximity-only system, i.e. only the subsets of RSSI measurements for packets transmitted with the power of -30 dBm were used.
- Using proposed fusion method, i.e. complete datasets containing RSSI measurements for packets transmitted with both -12 dBm and -30 dBm were used.

VI. Experiment Results

Experimental results show that Multi-Layer Perceptron Neural Networks underperform Random Forests in indoor positioning applications. Random Forests classifier provides the lowest overall average error as well as each of the quartile errors. It is worth to notice that Random Forests classifier achieves better results when mixed-mode input data (i.e. proximity-based and DCM-like) are used. This is in opposite to MLP, where the highest accuracy can be reached with the use of proximity mode only. It is also noticeable that in case of MLP classifier, the biggest averaged positioning error was achieved for the mixed mode.

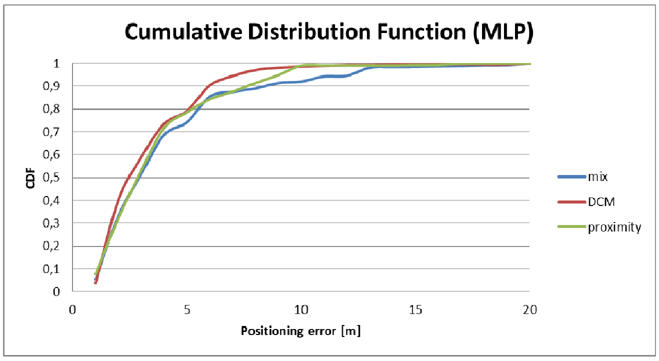


Fig. 9. Cumulative Distribution Function (CDF) of positioning error for MultiLayer Perceptron Artificial Neural Network classifier

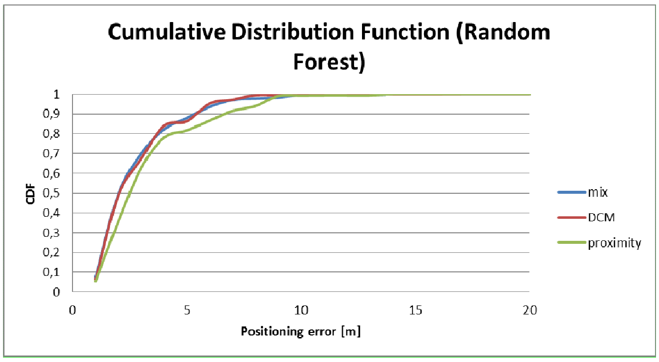


Fig. 10. Cumulative Distribution Function (CDF) of positioning error for Random Forests classifier

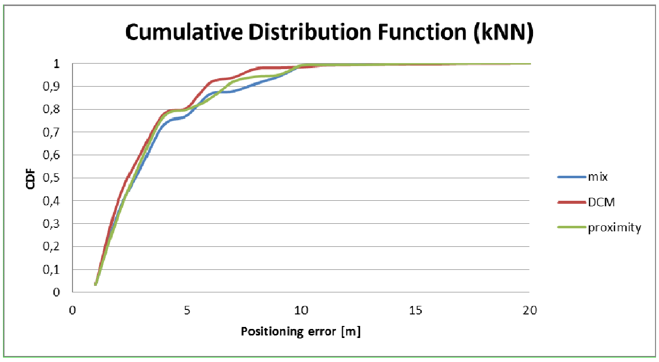


Fig. 11. Cumulative Distribution Function (CDF) of positioning error for k-Nearest Neighbour classifier

Simple kNN classifier outperforms MLP when average error is considered. On the other hand, the maximum positioning error (4th quartile) for kNN classifier was as high as 19.42 meters for DCM-like dataset, which is significantly higher than for Random Forest classifier.

Random Forest classifier takes all the benefits from combined proximity and DCM modes and outranked MLP and kNN in all accuracy indicators i.e. mean positioning error and the values for all considered quartiles.

Averaged positioning error and error quartiles for the three examined approaches and two proposed algorithms were summarized in Table I.

When CDF functions are considered (Fig. 9 to Fig. 11) a number of features might be observed. First of all CDF for Random Forest classifier outperforms CDFs for MLP and kNN while growth rate in the area of positioning error ranging from 0 to 10 meters is considered. This results in high accuracy in real applications, which is reflected in low average positioning error. It can be also observed that RF underperforms when proximity-only mode is used, however combining proximity mode with DCM methodology results in increasing positioning accuracy. On the other hand, combining proximity and DCM methodologies results in significant increase of location estimation inaccuracy when MLP classifier is involved.

Besides positioning accuracy, Random Forests are also computationally very efficient when compared to MultiLayer Perceptron network, especially when the training time is considered.

Table I.
Error Indicators of the Tested Positioning Methods

	-30 dBm			-12dBm			mixed -30 dBm and -12 dBm		
Indicator	MLP	RF	kNN	MLP	RF	kNN	MLP	RF	kNN
Average positioning error [m]	3.16	2.79	2.95	2.83	2.27	2.70	3.53	2.32	3.10
Average positioning error (25 %) [m]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average positioning error (50 %) [m]	2.24	2.24	2.24	2.24	2.00	2.24	2.24	2.00	2.24
Average positioning error (75 %) [m]	4.12	3.16	3.16	4.12	3.00	3.00	5.00	3.00	4.12
Average positioning error (100%) [m]	17.00	13.34	17.03	19.10	16.03	19.42	19.00	14.00	14.04

VII. SUMMARY AND CONCLUSION

In this paper indoor positioning system for short range radio communications network has been proposed. The system uses radio beacons transmitting packets with two different power levels of -12 dBm and -30 dBm. This approach gives possibility for joint use of positioning methods based on proximity detection and database search. While packets transmitted with output power of -12 dBm covers relatively large area, transmit power of -30 dBm strongly distinguish small areas of interest.

The positioning system combines proximity sensing and database search methods. The experiments conducted in a large office building resulted in average positioning error not exceeding 2.32 meters when Random Forest classifier was used with combined proximity sensing and database search methods. Since the system uses custom device coupling radio beacons with modern smartphones via Bluetooth connectivity, it is possible to present the results to the users in the form of voice messages.

Future development works assume incorporation of multi-system opportunistic positioning. As the result, the positioning algorithms will benefit from the use of data from generally available radio networks, like public Wi-Fi or mobile cellular telephony networks.

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