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Evaluation of a sectorised antenna in an indoor localisation system

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Abstract: Sectorised antennas (SA) integrated with low-power technologies have lead to significant improvement on localisation systems (LS) performance. A SA specially designed for localisation purposes is the Hive5, a platonic pentagonal patch-excited SA. This study presents the developed firmware and management application of an LS integrated with the Hive5. This LS performance is then compared with a typical wireless sensor network (WSN) LS based on four nodes. Both solutions are analysed within the same localisation environment and compared with the same supporting fingerprinting algorithm, an artificial neural network. Results show that LSs integrated with the Hive5 present clear benefits when compared with the WSN of four nodes in terms of resolution and obvious reduction of required reference units.

1 Introduction

Localisation systems (LS) are one of the fastest growing areas of electrical engineering today. These systems have been developed through several technologies, based on diverse techniques and supported by innumerable algorithms. The choice of previous settings is related to the main desired performance benchmarks for LSs such as: accuracy, precision, complexity, scalability, robustness, cost, power consumption and availability [1].

Despite of the large panoply of existing radio frequency (RF) LSs, they are highly influenced by one common factor: the antenna's performance. Reference unit antennas are commonly designed to be robust, inexpensive, impedance matched over the entire operational bandwidth, small and highly efficient. These characteristics are important for the correct performance of the antenna, which inherently have impact on the LS performance. Nevertheless, other antenna's characteristics such as radiation pattern and polarisation, should be carefully chosen according to the LS approach.

LSs based on wireless sensor networks (WSN) have been mostly integrated with omnidirectional and vertical polarised antennas [2–4], as presented in Fig. 1*a*. The omnidirectional radiation pattern is mainly justified by its uniform coverage, essential for lateration techniques. The vertical polarisation is preferred because of co-polarity under user azimuthal rotation. Nevertheless, diversity of radiation pattern and polarisation can significantly improve localisation as well as the communication systems' performance. These benefits can be achieved using independent directive antennas such as mechanical rotative and sectorised antennas (SA) operating its elements alternatively or by using different antenna array approaches such as phased, adaptive or even sectorised antenna arrays (SAA), [5], as presented in Fig. 1*b*. All of these SAs, when well implemented, can provide higher coverage, higher accuracy, increased system capacity, signal-to-noise ratio improvement, multipath rejection and reduction of required reference units (RUs) to the LS.

Several SAs have been presented in literature as using different localisation approaches, such as

- Narrow band SAA supported by signal processing algorithms [6];
- Ultra-wideband (UWB) SAA based on amplitude difference of the received pulse between each antenna element [7];
- UWB mono-pulse radar systems based on difference of received signal phase/amplitude and round time of flight [8];
- Switch beam, phase antenna array or mechanical rotation of a directive antenna performing a sweep of the beam over the localisation area [9–14].

In this paper an SA called Hive5, especially designed for LSs, is tested. This antenna was initially published in [15] and deeply analysed in [14]. This solution has benefits when compared with WSNs integrated with omnidirectional antennas, and it provides:

- Reduction of RUs number;
- Consequent reduction of LS cost;
- Addition of another measurement approach for the localisation process, angle of arrival (AoA);
- Higher range than a single RU.

SAs based on platonic structures have been previously presented in [6], a semi-dodecahedron antenna array. This antenna was specially designed to operate at 2.45 GHz and provides direction and polarisation selectivity. The

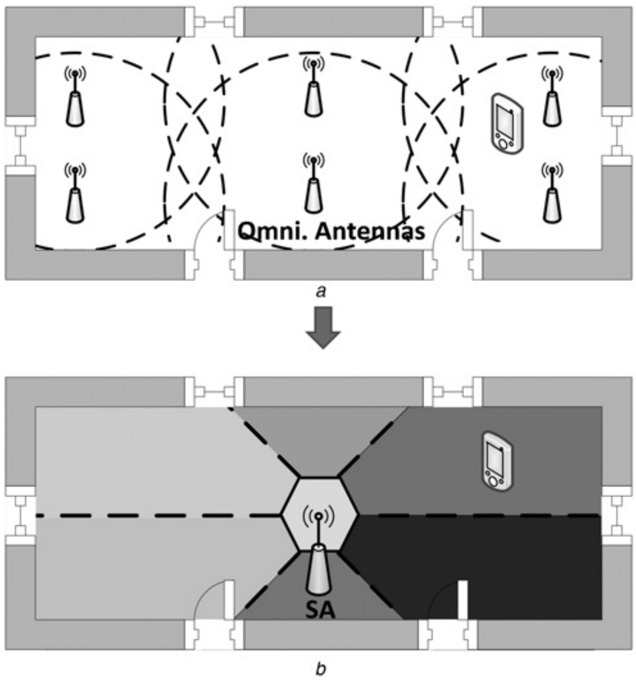

Fig. 1 *LS models*

a Based on WSN
b Based on SA

localisation process was presented with multiple signal classification (MUSIC) algorithm, adopting spectral decomposition of the covariance matrix of the power readings.

The main differences between the Hive5 and the previously cited antennas consist of a careful design that provides semi-spherical radiation pattern, higher gains with a maximum variation of 3 dB beam width over the radiation pattern and increased multipath rejection. These characteristics consequently provide higher coverage, nearly semi-spherical radiation pattern, reduced coupling between neighbour antennas and a consequent easier discrimination of the localisation sectors. The localisation approach is also different, as the analysis is based on a switch-beam antenna instead of on an array, significantly reducing the complexity and cost of the RU.

This paper also presents a performance comparison between the Hive5 and a WSN LS of four reference nodes. This comparison is performed under the same localisation scenario and fingerprinting approach, in this case, based on artificial neural networks (ANN), a common algorithm used for LSs based on WSNs [16].

The management and control application are also presented, providing the support for further analysis of other algorithms.

Based on the previous description, this paper is organised as follows: Section 2 briefly presents the Hive5 antenna and is followed by Section 3, where the localisation protocol is described. The next section presents the developed application for Hive5 calibration and operation. In Section 5 the measurements of the test bed are described in addition to the presentation of a comparison with a typical WSN LS based on ANNs, demonstrating the viability of the proposed antenna. Finally, some conclusions are presented in Section 6.

2 Hive5 antenna

The Hive5, presented in Fig. 2, is an SA formed by six pentagonal patch-excited antennas integrated into a pyramidal semi-platonic structure [15]. The six independent oriented antennas and the correct dimensioning of the metallic structure allow the combination of the RSS with AoA measurements.

The Hive5 can be used either as a switch beam antenna or as an SAA with appropriate signal processing algorithms, although, in this way, at the cost of a more complex system. The switched beam antenna approach provides a simpler and cheaper solution making it more suitable for low cost LSs. Besides the Hive5 antenna, this approach also requires the following components: a measuring RSS module, an SP6T RF switch, and low loss RF cables as presented in Fig. 3.

For the presented test a commercial system on chip was considered on the RU [17]; a SP6T as the RF Switch [18]

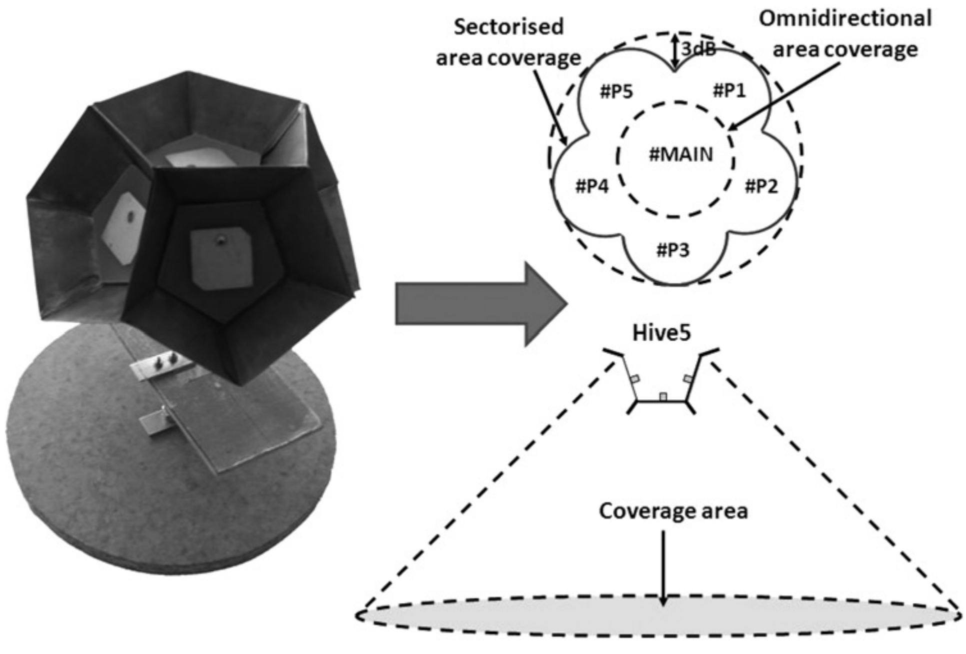

Fig. 2 *Hive5 antenna description*

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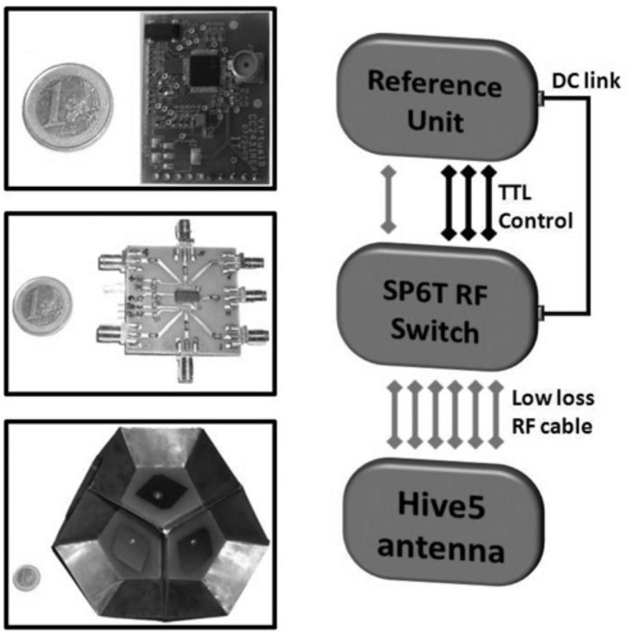

Fig. 3 *Implementation of Hive5 in a LS*

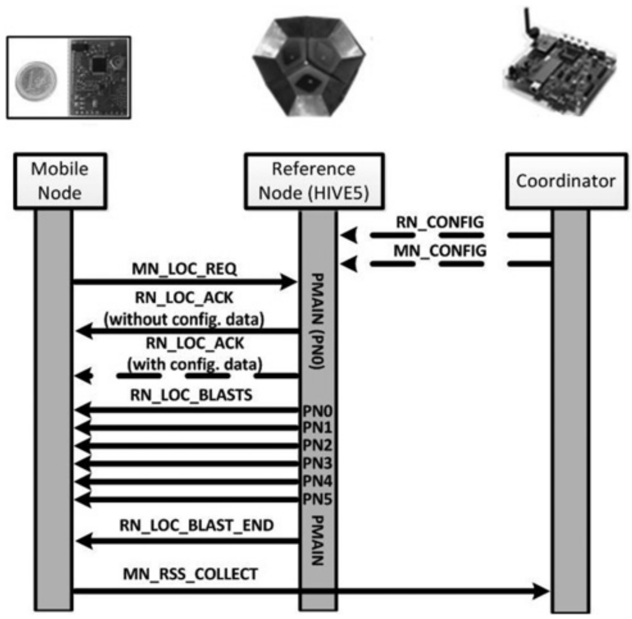

Fig. 4 *Localisation protocol description*

and semi-rigid cables of 18 and 23 cm with a measured transmission loss below 0.32 dB for considered lengths. These cables are used for the Hive5, RF-Switch, and RU interconnections.

3 Hive5 localisation protocol

The Hive5 is an antenna suitable for LSs that requires a single RU. Nonetheless it needs to be integrated into a high and central position on the localisation scenario for the system to achieve efficient performance. The developed protocol consists of a simple network of three elements: a mobile unit or node (MN), which is the element to be located; a RU or node (RN), which is the controller of the Hive5; and a coordinator, which is the gateway to the PC running the LS application.

3.1 Mobile node

After registratering into the network, the MN sends a localisation request (MN_LOC_REQ) to the WSN waiting for acknowledgement from the RN (RN_LOC_ACK). This message may include configuration data as a payload. Then, the MN listens to the channel for Hive5 blasts (RN_LOC_BLAST) and subsequently, the end process message (RN_LOC_BLAST_END). Each of the previous messages send the identification of the transmitter Hive5 element (PN0 to PN5) as a payload. The MN measures the RSS of each message and associates it to the Hive5′s transmitter element. After the collection of RN_LOC_BLASTs and subsequent RN_LOC_BLAST_END the RSSs and correspondent Hive5 elements' identification are sent as unicast to the coordinator (MN_RSS_COLLECT). After the RSS collection is sent, the MN enters into a low power consumption mode (sleep Mode) where the transceiver and MCU are turned off. The MN wakes up after a pre-defined interval and this process is cyclically repeated. The expired intervals and sleep time are configured within the reception of the RN_LOC_ACK message.

3.2 Reference node

The RN permanently stays into a polling mode listening for WSN messages. It can receive messages from the coordinator (RN_CONFIG and MN_CONFIG) to configure the RN number of blasts and/or transmission interval and the MN expiration or sleep intervals. For localisation processes the RN initially receives a localisation request from the MN (MN_LOC_RQT). After receiving this message, the RN replies with an acknowledgement (RN_LOC_ACK) which may contain configuration data. After this handshake, the RN sequentially activates each antenna element of the Hive5 to send blasts (RN_LOC_BLAST). When this process finishes, the main antenna element (PN0) is activated to send a confirmation of the transmission process end (RN_LOC_BLAST_END).

3.3 Coordinator

The WSN coordinator acts as a simple gateway with a PC running the LS application. The coordinator receives WSN messages and forwards them to the serial port and vice-versa. All of the commands, selected on the application that will be described in next section, can be sent to the WSN by the intermediation of the coordinator. A simplified representation of the localisation protocol is shown in Fig. 4.

4 Application

The management application that controls the LS was developed to perform four main operation options: detection, calibration, testing, and configuration.

This application was developed using Java language because of its interoperability capabilities simplifying its implementation in different operating systems. The first option (detection) provides an online localisation based on different algorithms that can be selected by the user, such those based on propagation models or fingerprinting, in this case, ANNs based.

Detection provides the visualisation of collected RSSs and corresponding estimated localisation; calibration provides the chance to record the collected RSSs for further offline calibration; testing provides the chance to analyse the response of different WSN devices; the configuration option allows for the configuration of WSN devices and an optional forwarding of the MNs position to a remote database, which is similar to the work developed in [19].

All of the previously described options provide the basis for a correct operation and control of the Hive5 antenna according to the different localisation scenarios to which it can be applied.

5 Results

To test the two LS solutions (using Hive5 and a typical WSN of four nodes) a testing scenario (TS) with dimensions of 7 m × 4 m × 2.5 m was chosen, as suggested in Fig. 5.

The Hive5 was inserted at a height of 2.3 m nearly at the centre of the room and the four WSN nodes were placed on the ceiling, between 1.5 and 1 m distant from the sidewalls. With the infrastructure settled, a MN integrated with a faced up circular polarised patch antenna was used as measuring unit. 10 RSSs measurements were made from a height of 75 cm over the entire testing area. Each of the measurement points is presented by the lines intersection in Fig. 5.

After all the measurements were collected by the MN, an average RSS mapping of each Hive5 element was obtained, as shown in Fig. 6.

PN0 represents the main element (faced down) of the Hive5. This element presents cross-polarisation with the MN antenna, making its sectorial identification difficult. In all of the other elements, five clear areas are identified, as seen in Fig. 6. Based on an identical process shown in Fig. 4, but recurring to WSNs instead of SAs, an average of the RSS mapping for each position was also obtained. For this mappings all four RNs were considered with linear polarised patch antennas. The achieved RSS collection is presented in Fig. 7.

The calibration of the ANN was performed with the RSS collection acquired [16].

This specific test considered a supervised learning ANN with a group of training sets (pairs of inputs and known outputs, targets). After the network's training period (made

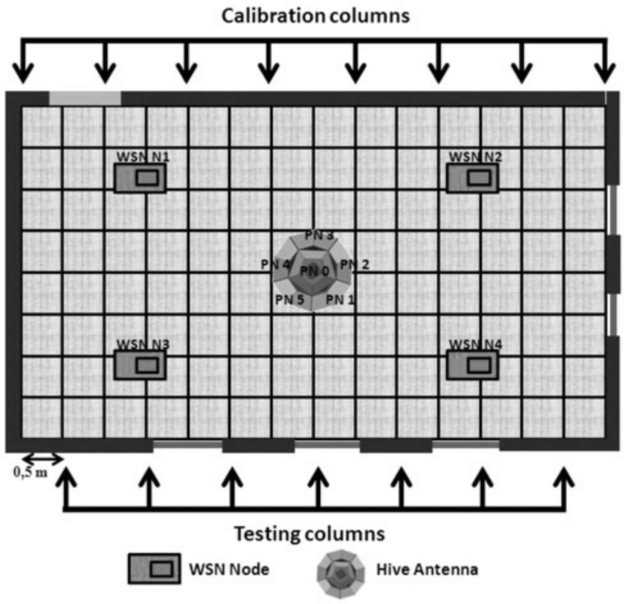

Fig. 5 *TS representation*

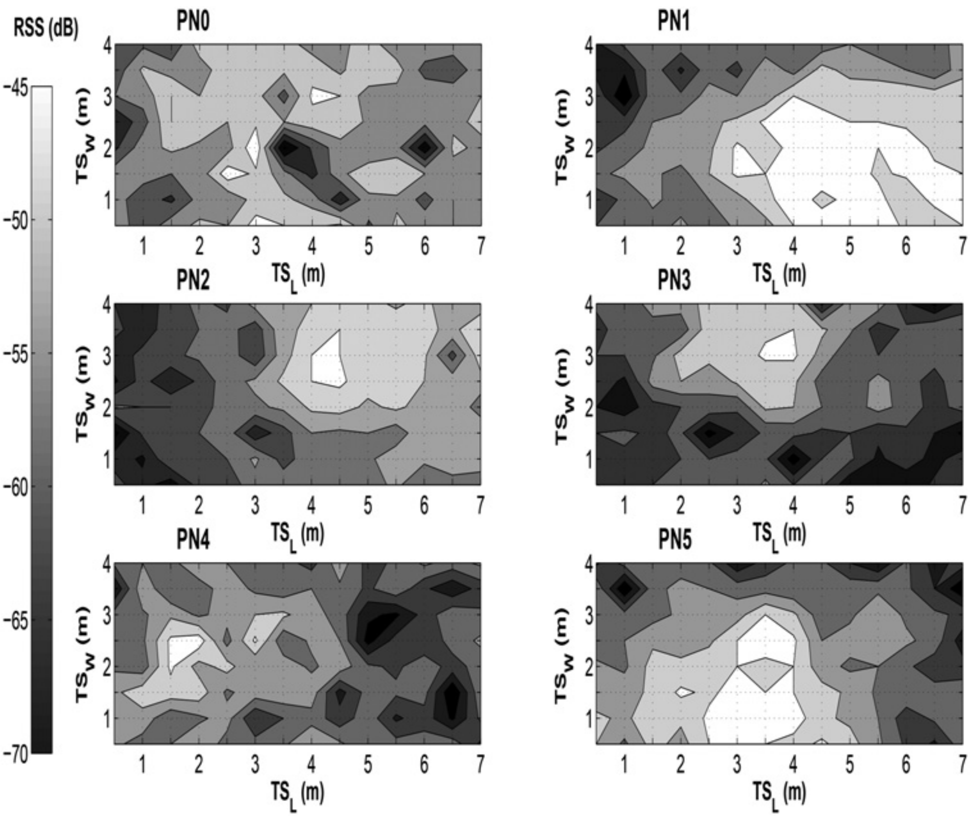

Fig. 6 *RSS measurements with Hive5 Antenna*

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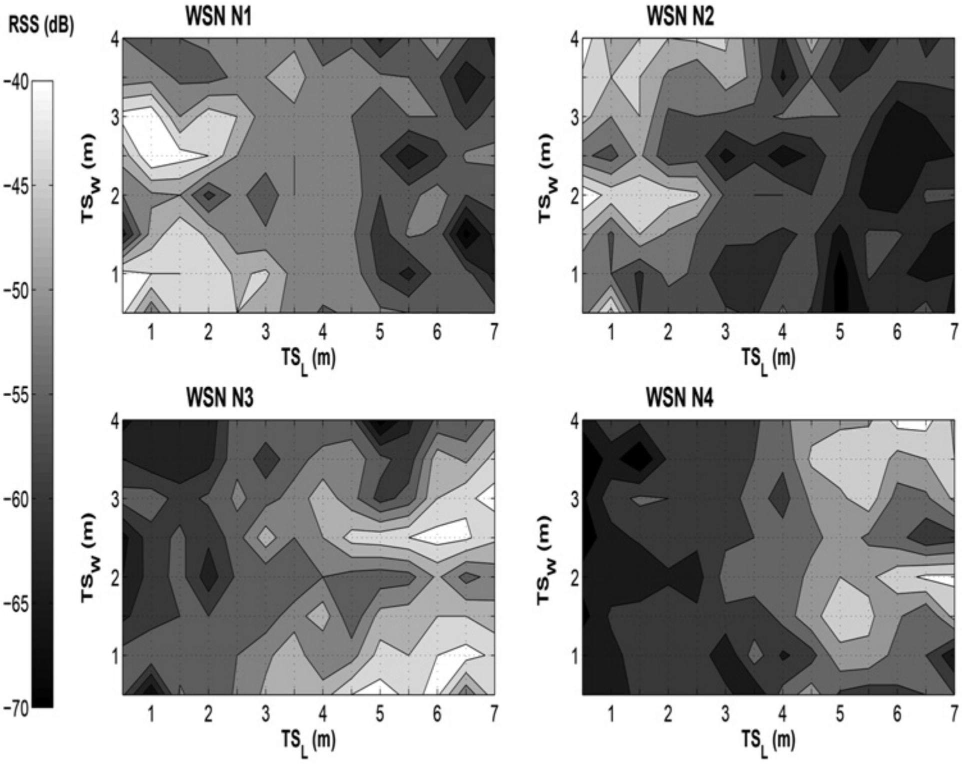

Fig. 7 *RSS measurements with WSN of four RNs*

during an offline phase), the system became ready to respond to diverse input collections (online phase).

The inputs for this system were a collection of RSSs, six for the Hive5 and four for the WSN, defining the ANN input layer dimension as six and four neurons, respectively. Even of considering a larger input layer for the Hive5, only three to four RSS measurements provide effective information to the ANN. For this reason, this test is considered a fair comparison with an ANN applied to the WSN of four nodes. This ***RSS*** input vector is described as

$$\boldsymbol{RSS}_i = (a_{i1},\ a_{i2},\ \ldots,\ a_{\text{in}}) \tag{1}$$

where a_{ij} corresponds to the ***RSS*** collection from point i, and RN identifier j. Like this, the complete RF fingerprinting matrix ($\boldsymbol{M}$) of m elements is given by combining spatial information with the respective collected ***RSS*** vector given as

$$\boldsymbol{M} = x_i,\ y_i,\ \boldsymbol{RSS}_i,\ i = 1,\ 2,\ \ldots,\ m \tag{2}$$

The outputs of the systems were collected from the position of the tested MN, being represented as X and Y coordinates. In this way, the ANN output layer was defined by two outputs. The number of hidden layers was defined as one because the increase of layers did not demonstrate relevant improvements in this test.

To train the ANN, the odd columns were considered for calibration whereas the even columns were considered for testing, as shown in Fig. 5.

To test the performance of the ANN, its dependency to two of the most influential parameters was analysed, namely the training algorithm and the number of neurons of the hidden layer. One single layer was considered because relevant improvements, consequent from the increase of hidden layers, were not clearly presented in this test.

Although nine training algorithms were analysed, in this paper only the three which achieved the best results are presented, namely the gradient descent with adaptive learning-rate back-propagation (GD_ALR_BP), gradient descent with momentum back-propagation (GD_M_BP) and Levenberg-Marquardt back-propagation (LM_BP).

The other parameter considered, which highly influenced the ANN performance, was the number of neurons per hidden layer. In order to avoid over fitting the ANN, an analysis of the optimum number of neurons was performed. As shown in Fig. 8, the best compromise between calibration and testing error for the Hive5 was achieved with seven neurons, that being the best performance achieved with the GD_ALR_BP algorithm.

For standard gradient descent algorithms the learning rate is held constant throughout training. The performance of the algorithm is very sensitive to the setting of the learning rate being not practical to determine the optimal learning rate setting before the training. GD_ALR_BP algorithm overpasses this problem because it updates the neurons

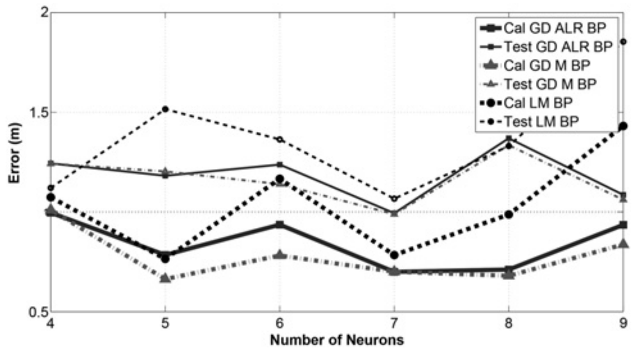

Fig. 8 *Hive5 ANN error dependency with number of neurons*

weight and bias values according to the adaptive learning rate. A detailed description of measured errors is shown in Table 1 and presented in Fig. 9.

In the implementation of the WSN with four nodes the best compromise achieved was with five neurons, that also achieved the best performance with GD_ALR_BP algorithm as shown in Fig. 10. A detailed description of measured errors for this case is shown in Table 2 and presented in Fig. 11.

As demonstrated by previous results, the ANN performance using the Hive5 antenna presented better results when compared with a WSN of four nodes under the same localisation scenario. The best performance was achieved with seven neurons for the Hive5 and with five neurons for the WSN of four nodes, both with the GD_ALR_BP algorithm. The Hive5 also showed performance advantages, specifically the number of needed nodes, which are significantly reduced with the need of one single node. One other test was performed considering other sets of calibration and testing points. In this case, two crossing groups of alternate points were considered, instead of alternate columns. Nonetheless, better results were achieved by using the first approach.

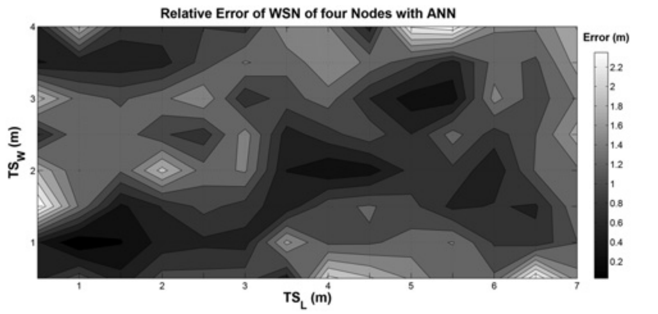

Fig. 11 *WSN ANN error for GD_ALR_BP, five neurons*

Table 1 Hive5 ANN error with GD_ALR_BP and seven neurons

Calibration error				Testing error			
Mean	Std	Min	Max	Mean	Std	Min	Max
0.699	0.50	0.11	2.02	0.99	0.55	0.09	2.61

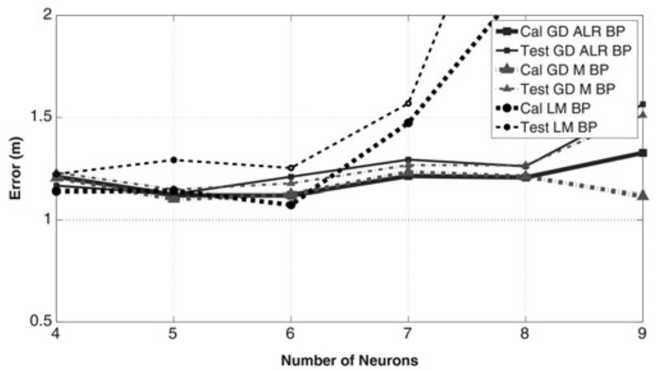

Fig. 9 *Hive5 ANN error for GD_ALR_BP, seven neurons*

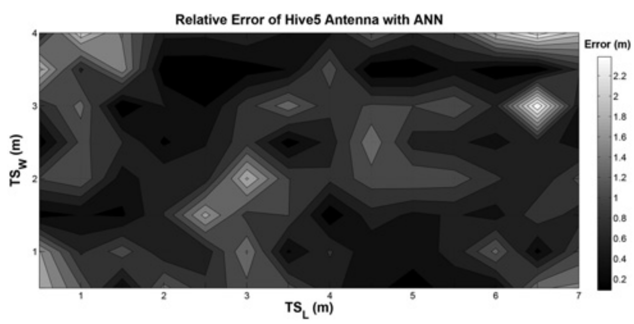

Fig. 10 *WSN ANN Error dependency with number of neurons*

Table 2 WSN ANN error with GD_ALR_BP and five neurons

Calibration Error				Testing Error			
Mean	Std	Min	Max	Mean	Std	Min	Max
1.121	0.47	0.44	2.58	1.12	0.55	0.03	2.54

6 Conclusion

This paper analyses a SA in an indoor environment in comparison with a typical WSN of four nodes. The antenna, firmware and application are presented, also as the comparison of the performance of the Hive5 with a WSN of four nodes under the same fingerprinting algorithm, an ANN. As shown by RSS measurements, the Hive5 provides a better solution when compared with the WSN concerning the resolution and number of required RNs, which can provide a cheaper localisation solution. It was verified that a gradient descendent with adaptive learning-rate back-propagation GD_ALR_BP algorithm provided the best localisation performance for both approaches, under the considered conditions. Based on this RSS measurements analysis, GD_ALR_BP can be identified and considered as a proper ANN learning algorithm for LSs in indoor environments.

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