Radio Environment Maps for Military Cognitive Networks: Density of Sensor Network vs. Map Quality

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Abstract. In this paper we present the dependency between density of sensor network and map quality in the Radio Environment Map (REM) concept. The architecture of REM supporting military communications systems is described. The map construction techniques based on spatial statistics and transmitter location determination are presented. The problem of REM quality and relevant metrics are discussed. The results of field tests for UHF range with different number of sensors are shown. Exemplary REM maps with different interpolation algorithms are presented. Finally, the problem of density of sensors network versus REM map quality is analyzed.

Keywords: Cognitive radio · Radio Environment Map · Spectrum monitoring · Density of sensor network · Deployment of sensors

1 Introduction

In recent years, in many fields of technology there has been a growing trend towards creating intelligent solutions that autonomously make decisions about their actions. This trend can also be noticed in wireless communications. It is worth mentioning here such solutions as self-organizing networks [1, 2], disruption-tolerant networks [3], dynamic spectrum management [4, 5] and cognitive radio [6]. In military communications new technical solutions are adopted with great caution as they are used in very specific conditions and must be extremely reliable. Military wireless networks must be immune to deliberate interference and operational even in the case of systematic destruction of telecommunications infrastructure.

The problem of efficient frequency management in common operations has been noticed by NATO and, as a consequence, the IST panel has established a working group whose tasks include among others checking potential benefits resulting from the implementation of the Radio Environment Map concept.

The aim of the IST-146 RTG-069 group is to work out a concept of REM enabling their users to obtain the spectrum operational picture and to minimize the level of interferences between wireless systems of coalition forces. One of the main goals of the

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research group is to define the architecture of the system and to specify interfaces to other systems in the area of frequency management.

According to the NATO IST RTG-050 plan, REM is also needed to make a significant step towards a coordinated spectrum management system in NATO [4].

In the paper we discuss the concept of REM and the problem of the number of sensors from the point of view of tactical operation. We also present exemplary maps created using different interpolation methods and analyze how the number of sensors affects the quality of the maps. Additionally we focused on the possibility of localization of the TX antenna in reference to selected interpolation techniques.

The rest of the paper is organized as follows: related works (Sect. 2), map construction techniques (Sect. 3), test scenario and exemplary maps (Sect. 4), analysis of the results (Sect. 5) and conclusions (Sect. 6).

2 Related Works

In general, REM is considered as a database which maintains comprehensive and up-to-date information on the radio spectrum. It is assumed that this information is composed of geographical features, available services, spectral regulations, positions and activities of radios, policies adopted by the user and/or service providers, and knowledge from the past [7].

The simplified architecture of REM excerpted from [8, 9] and adapted to military applications is presented in Fig. 1. REM architecture comprises the following modules: REM Manager, REM storage and data collection, REM Acquisition, sensors and GUI. REM Manager processes the data and controls the REM database in terms of measurement configuration, e.g. monitoring subranges, measurement mode (continuous or on request), active sensors. REM storage and collection module is an interface between the database, REM acquisition modules and REM Manager. REM acquisition modules are interfaces to various systems of sensors.

In the literature [11] sensors are generally named MCDs (Measurement Capable Devices). MCDs are controlled through REM Acquisition modules and monitor spectrum. In civilian applications the function of MCDs can be performed by various devices with measurement capability, such as simple mobile phones, smart phones, notebooks, etc.

When military systems are considered, spectrum measurements can be taken by dedicated receivers, cognitive radios, Electronic Warfare (EW) systems or Intelligence, Surveillance, Reconnaissance (ISR) systems [10, 18].

In the literature on the topic the spectrum sampling method for REM has not been thoroughly researched. Although the process of collecting the results of measurements to construct REM can be carried out by dedicated sensors with fixed positions and mobile devices (e.g. cognitive radios), the resources of mobile devices are more limited since they have to use their battery efficiently [17]. Therefore, the problem how the density of sensor network affects the quality of the REM must be addressed.

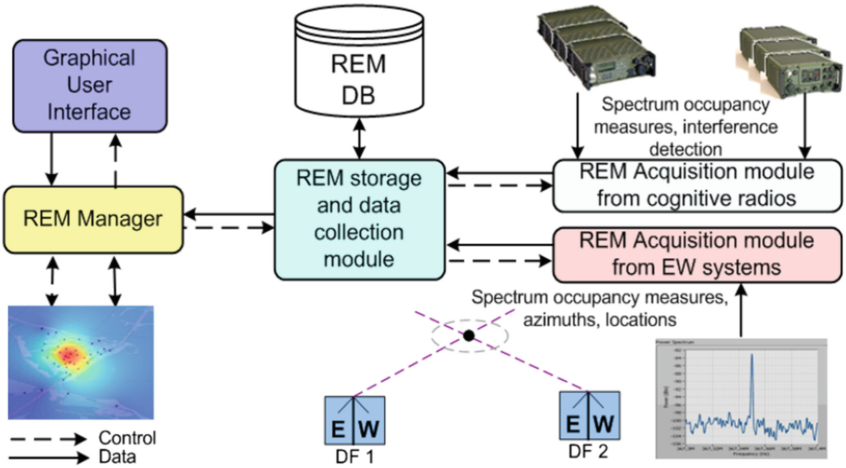

Fig. 1. REM architecture to support tactical operation [10]

In [13] the authors performed an experiment in real conditions whose aim was to determine the position of a transmitter operating at 800 MHz frequency with the application of the indirect method. The transmitter was placed inside a grid consisting of 49 nodes in a 7 × 7 arrangement, spaced 5 m apart. The results of measurements and calculations showed that at least 20 randomly selected sensors are necessary in order to determine the position of the transmitter with sufficient accuracy. In such a case the error of determining the position of the transmitter was about 1.5 m. When the results of measurements from 46 sensors were taken into account, the error of position determining decreased to about 1 m, which is 20% of the distance between the sensors in the grid.

In [14] the authors discussed a method of searching for White Spaces in UHF band (470–900 MHz) which could be used for Cognitive Radio (CR). Some field tests were performed with 100 measurement units deployed in the area of 5 km^2 and distributed in two ways: regular lattice (Cartesian) and pseudo-random. The authors noticed the relation between the number of measuring sensors and the required terrain resolution of the REM map being created and the number of CR users per square km.

In [15] the authors presented three methods of creating REM: path loss based method, Kriging based method and their own method. To compare the efficiency of the proposed methods a series of simulations were performed for scenario with: (a) one transmitting node, (b) 81 sensing nodes and (c) 8 validating nodes which do not overlap with the 81 sensors. All the nodes were deployed on the area 70 m by 70 m. To assess the quality of the created REMs the Root Mean Square Error (RMSE) was calculated for 8 validating nodes.

The accuracy of determining the location of the transmitter in meters was used as a measure of the quality of REM maps in [16]. The environment considered in the research work was a simulated urban macro-cell square area of 1 km^2. In this area one transmitter and up to 20 measuring sensors were placed randomly. REM maps were developed using two indirect methods: one based on received signal strength (RSS) and the other one based on received signal strength difference (RSSD). The authors confirmed a noticeable improvement in the quality of REM maps when the number of sensors is increased to 14–20 per km^2.

In the literature on the topic both kinds of methods of map creation are analyzed, that is the direct methods and the indirect methods, but it seems that the indirect methods prevail. In our paper, however, we deal with the REM maps created with the use of a few selected direct methods, which are described in the next chapter.

In order to assess the quality of REMs with different numbers of sensors used for the interpolation in our research work we used data obtained from real field tests and RMSE as a quality metric, similarly to [15]. The size of the area (approx. 4 km^2) was similar to the one presented in [14]. Although the number of sensors was smaller than the number typically analysed, it was comparable to [13] and [16].

It is worth noting that our research differs from the research described in the literature not only in terms of the number of sensors used but also the manner of their distribution. The reasons for these differences stem from the fact that the scenarios which we considered reflect networks used during small tactical operations, i.e. dozens of sensors operating in the area of several square kilometres. In military operations, the role of sensors is played by cognitive radio stations, and therefore the tactical situation determines their distribution. The scenarios presented in the literature usually assume that there are hundreds of sensors spaced quite regularly or arranged in controlled manner.

3 Map Construction Techniques

In the literature on the topic there is a description of three main categories of the REM construction techniques, namely *direct*, *indirect* and *hybrid* [11, 12]. *Direct* methods, also called *spatial statistics based methods*, are based on the interpolation of the measured data, while *indirect* methods, also known as *transmitter location based methods*, apply transmitter location and propagation model to obtain the estimated value. *Hybrid* methods combine both manners.

Spatial statistics based methods use measurement data taken at certain locations. In the case of REM the measurement is done at the location of the sensors. It is understandable that placing sensors in all required locations is impractical or simply impossible. For this reason samples from sensors are used as an input for the estimation process that can employ different kinds of techniques.

When REM is considered the most promising estimation techniques described in the literature are as follows: Nearest Neighbor (NN), Inverse Distance Weighting (IDW) and Kriging.

The Nearest Neighbor method is considered to be one of the simplest methods but it offers little accuracy. NN uses Thiessen (or Voronoi) polygons, which are defined by boundaries with equal distances from the points at which measurements were taken. A specific feature of these polygons is the fact that their boundaries are exactly in the middle of the distance between neighboring points.

IDW method is based on the assumption that the signal value P_1 at a given point (x_1, y_1) is much more dependent on the values in the nearest measurement points than on samples taken at distant points. To interpolate the signal value the IDW uses weighting factors w_i that are inversely proportional to the distance between the given point (x_1, y_1) and the sampling point (x_i, y_i) and raised to the power p. The power p determines how the weighting factors decrease with the distance. If the power p value is set high, the points which are close/nearby have stronger impact. When the power p value is set at zero, regardless of the distance, the weighting factors remain at the same level. In the rest of the paper we use the following notation for IDW method: IDW px where x is the power.

Kriging is one of the geostatic methods of interpolation. Like IDW, Kriging uses weighting factors but they are determined on the basis of the semivariogram. This semivariogram is based on the distance between measurement points and the variation between measurements of signal levels as a function of the distance. Kriging is considered to be the most accurate, though quite a complex method of interpolation.

In the literature of REM the use of Kriging in combination with another method of the signal level determining or the modification of Kriging is proposed [19, 20].

A more detailed description of the estimation techniques mentioned above is presented in [10].

4 Test Scenario and Exemplary Maps

In order to investigate the impact of the number of sensors on the REM quality several tests were conducted for UHF frequency band. First, measurements were taken in a real environment with 39 sensors to get input data and then, exemplary maps were created using different construction techniques, namely Nearest Neighbor, IDW and Kriging. After that, the analysis of calculated Root Mean Square Error (RMSE) for various numbers of sensors was made.

To assess the quality of the maps created with the selected interpolation techniques we analyzed the results for three scenarios with different number of sensors each, see Table 1. Each of the three scenarios consisted of 2 tests which were performed with different (random) deployment of sensors. It is worth noting that the sensors were arranged irregularly due to the fact that the measurements were taken in a real environment.

Table 1. Scenarios and tests for RMSE analysis

Number of sensors used for interpolation per number of control sensors	The name of scenario	The name of test
13/26	Scenario_13	Test_13a
		Test_13b
20/19	Scenario_20	Test_20a
		Test_20b
26/13	Scenario_26	Test_26a
		Test_26b

The initial distribution of 39 sensors is shown in Fig. 2. For the interpolation process the sensors selected in each test were chosen in a random process. For remaining sensors, in each test, the differences between the measured and the interpolated signal level were compared and used for calculating the RMSE. Finally, average values of the RMSE were calculated for each scenario.

In order to perform measurements in a real environment we established the test bed composed of a transmitting part and a receiving part.

The transmitting part of the system consisted of a signal generator connected to a controlling computer, an amplifier and an antenna mounted on the roof of a building at the height of 8 m.

The receiving part consisted of an antenna installed on a vehicle, a radio receiver and a computer controlling the receiving operation and recording the results of the measurements. The antenna was installed at the height of 3 m. The vehicle was moving within a preliminarily selected area, Fig. 2. The following configuration of the testbed was used: (1) UHF frequency: 1997 MHz, (2) modulation type: CW, (3) output power: 10 W, (4) measured parameter: avg. RSS, (5) number of averages: 10, (6) antenna type: omnidirectional.

The measurements were taken in the area of Zegrze lake in Central Poland (the area of approximately 4 km^2 presented in Fig. 2). The test area was diverse in terms of coverage (partly an open meadow neighboring a forest and partly an urbanized area with medium-sized and high buildings).

Fig. 2. Deployment of the sensors and position of the TX antenna

Some exemplary maps for scenario with 26 sensors constructed with four interpolation techniques are presented in Fig. 3.

The NN method (Fig. 3a) creates polygons around each sensor. The size and the shape of the polygons depends on the number and the arrangement of neighboring sensors. Within each polygon the signal strength takes the value measured by the sensor. For this reason the signal strength changes suddenly at the edges of polygons, e.g. between the orange polygon close to the center and the dark blue one to its right.

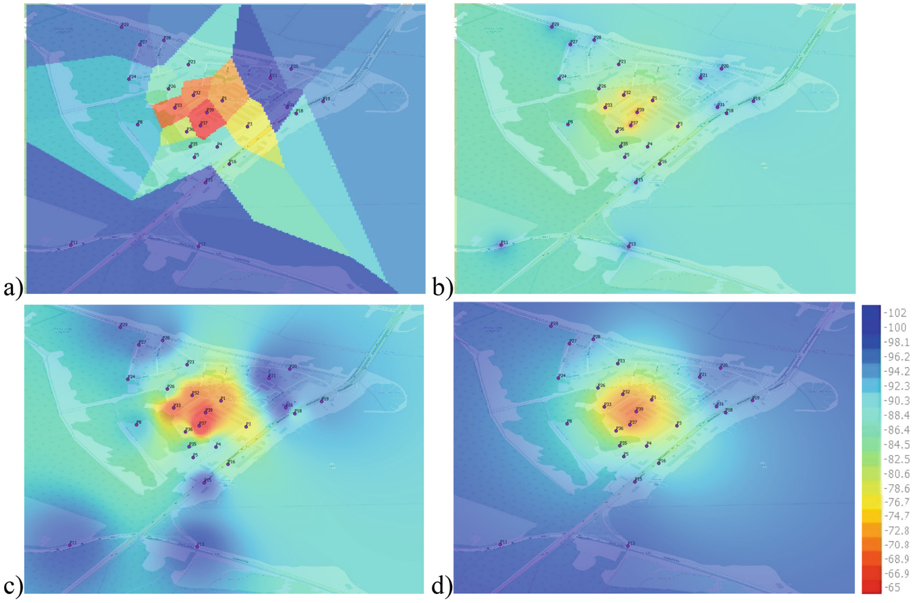

Fig. 3. Exemplary maps for scenario with 26 sensors constructed with different interpolation techniques (signal value in dBm): (a) NN, (b) IDW p1, (c) IDW p3, (d) Kriging (Color figure online)

The IDW method (Fig. 3b and c) generates smoother maps when compared to NN. However, the bull's-eye effect occurs and the size of eyes depends on the power *p* used in the interpolation process. The estimation of the signal strength is quite accurate if the power *p* is set at 3 or higher and the sensors are deployed densely.

When Kriging is applied (Fig. 3d), the signal value changes smoothly within the whole area. Kriging seems to be a method which is least sensitive to the deployment of the sensors. Neither bull's-eye effects nor rapid changes in the signal value are observed even if the sensors are deployed sparsely or irregularly.

In the presented scenario the position of the TX antenna can be determined with the accuracy of approximately:

- 350 m for IDW p1,
- 300 m for NN,
- 250 m for IDW p3,
- 150 m for Kriging.

Exemplary maps for IDW p3 interpolation technique for various numbers of sensors are shown in Fig. 4. The lowest signal level is represented by the dark blue color while the highest level - by the red color. The map presented in Fig. 4a (13 sensors) seems to be unnatural since there is quite an extensive yellow and green area representing the medium signal strength, even for those regions that are distant from the TX antenna. The bull's-eye effect with the dark blue color is present in a few places only. The general conclusion is that there are too few sensors and that they are deployed too sparsely.

The map shown in Fig. 4b was created with the input data from 20 sensors. There is more of bull's-eye effect with the dark blue color surrounding the central part of the map where the source of emission was located. However, there are quite many regions further away from the TX antenna which are marked with yellow and green color.

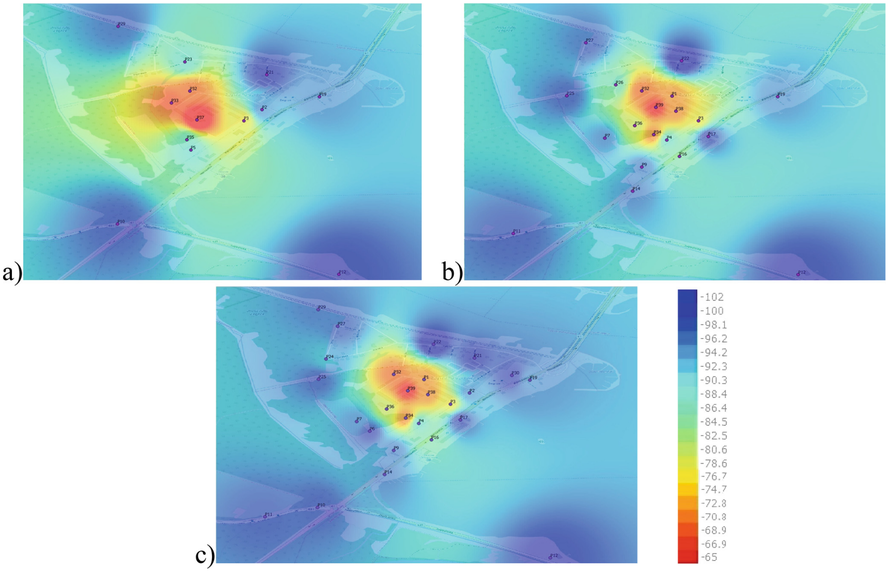

Fig. 4. Exemplary maps constructed for IDW p3 interpolation technique and various numbers of sensors (signal value in dBm): (a) 13 sensors, (b) 20 sensors, (c) 26 sensors (Color figure online)

The map presented in Fig. 4c (26 sensors) looks more natural when compared to the maps shown in Fig. 4a and b. Since the sensors are arranged much more densely the red-orange center of the map is quite regularly enclosed by the dark blue color of the bull's-eye effect. Moreover, the increased number of sensors caused better reflection of the signal level for these areas that are distant from the TX antenna (medium low signal level imitated by the blue color).

Exemplary maps for Kriging interpolation technique for various density of sensor network are shown in Fig. 5. The dark blue color represents the lowest signal level while the red color - the highest. As the number of sensors increases, the map seems to look more natural, that is the area where the signal level is high (the red-orange color) becomes smaller, whereas regions around the TX antenna where the signal level is low become more distinct (marked with the dark blue color). Moreover, if there are more sensors, the position of the TX antenna can be determined with better precision. This effect can be easily noticed when the sizes of the red-orange areas in Fig. 5c and a are compared.

A more detailed analysis of the impact of the density of sensor network on the quality of maps mentioned above is given in the next section.

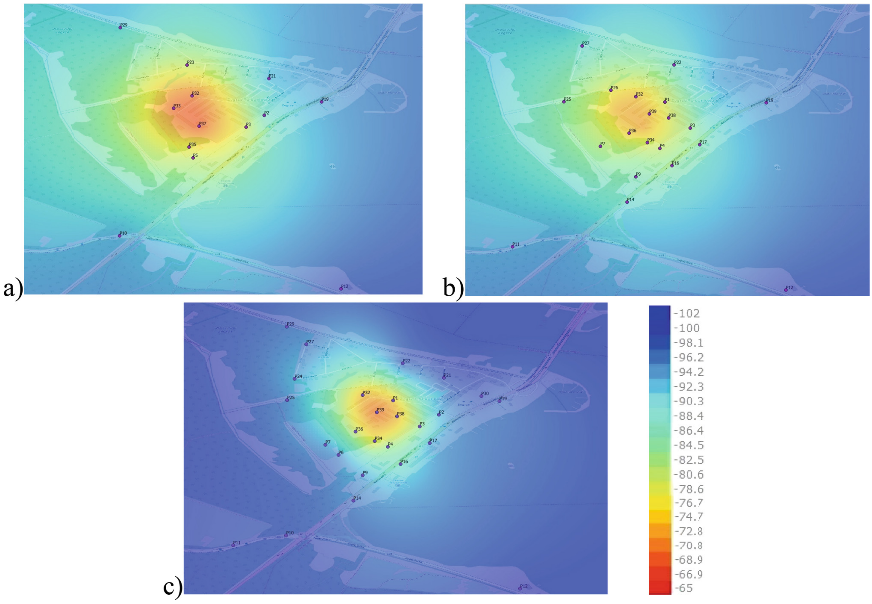

Fig. 5. Exemplary maps constructed for Kriging interpolation technique with various numbers of sensors (signal value in dBm): (a) 13 sensors, (b) 20 sensors, (c) 26 sensors (Color figure online)

5 Analysis of the Results

The RMSEs calculated for Nearest Neighbor, Kriging and IDW methods with power p from 1 to 6 are shown in Fig. 6.

Figure 6a presents the results for the scenarios with 13 sensors. The differences between the results for individual tests are quite significant. The comparison shows that, irrespectively of the interpolation technique, the RMSE values are smaller for Test_13b than for Test_13a. The RMSE for Test_13a reaches 9.1 dB for IDW p3 and 7.8 dB - for Kriging. The RMSE for Test_13b reaches 10.95 dB for IDW p3 and 9.6 - for Kriging. The results for NN method are comparable for both tests (RMSE oscillates around 11.85 dB). When Kriging was applied, the RMSE values were the smallest for both compared tests.

The results for the scenario with 20 sensors are shown in Fig. 6b. Independently of the applied interpolation technique, the RMSE values are smaller for Test_20a when compared to Test_20b, except the results for IDW p1, which are in fact the worst case (RMSE over 10 dB). The RMSE for Test_20a for IDW p3 reaches 8.5 dB and for Kriging - 6.7 dB, while for Test_20b the RMSE reaches 8.8 dB for IDW p3 and 8 dB for Kriging. For both compared tests in this scenario: (a) Kriging offers the best results, (b) RMSE drops as the power *p* increases for IDW method. The differences between the results for individual tests are within 1.3 dB.

Figure 6c presents the results for the scenario with 26 sensors. For both tests the RMSE values are much higher for NN and IDW p1 (between 8.8 dB and 11 dB) than for other interpolation techniques (RMSE from 6.2 to 7.5 dB). In the case of Test_26b the smallest RMSE occurs for Kriging (6.25 dB), while in the case of Test_26a the RMSE reaches the minimum value for IDW p4 (6.3 dB).

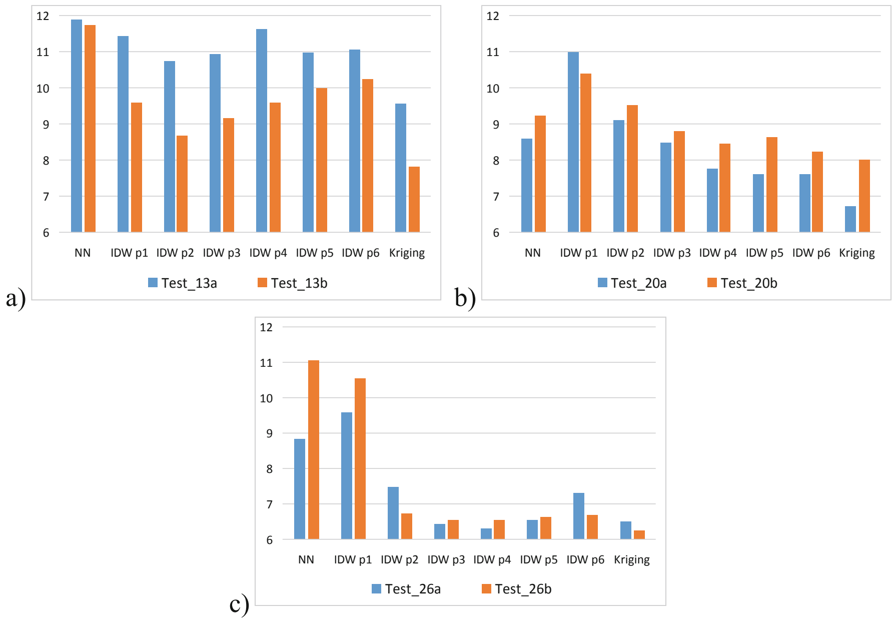

Fig. 6. RMSE (in dB) for selected interpolation techniques: (a) scenario with 13 sensors, (b) scenario with 20 sensors, (c) scenario with 26 sensors

The average values of RMSE for each scenario are shown in Fig. 7. The effect of the drop in the RMSE as the number of sensors increases is clearly visible for IDW with power *p* higher than 1 and for Kriging interpolation technique. When IDW p1 method was applied, the benefit of having more sensors in the network was inconsiderable. If NN method was applied, the smallest RMSE value occurred for the scenario with 20 sensors. In general, the trend in the changes of RMSE confirms that placing more sensors in the network makes the quality of REM higher.

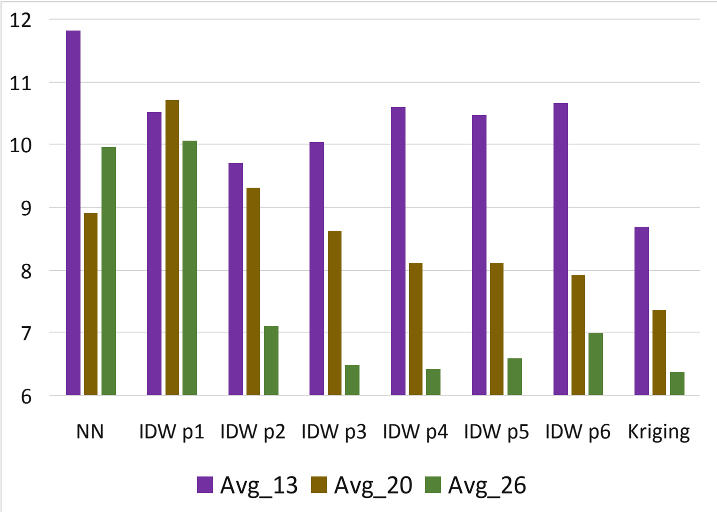

Fig. 7. The average RMSE (in dB) for selected interpolation techniques and scenarios with 13, 20 and 26 sensors

6 Conclusions

The quality of maps depends on several factors, among others the density and regularity of deployment of sensors, the distance between sensors, the propagation environment and the interpolation technique. In this paper we analyzed the impact of the number of sensors on the REM quality.

In the literature on the subject mainly scenarios with several hundred measurement points located in the area of around 5 km^2 are studied. In some real applications this number is much lower, e.g. reaching dozens of sensors in the area of approximately 4 km^2. That is why we focused on the scenarios with a small number of sensors that reflect, for example, a small-scale tactical operation or CR networks operating in suburban areas.

In our research work we used data from real field tests with 39 sensors deployed within the area of 4 km^2. We analyzed results of the tests with different numbers of sensors (13, 20 and 26) used for the interpolation process. For each scenario two tests with various arrangements of sensors were analyzed. To create REM maps the following interpolation techniques were applied: NN, IDW and Kriging. To assess the quality of maps the calculated RMSE values were compared. In general, the increase in the number of sensors from 13 to 26 caused a visible improvement in the quality of REM maps. The average RMSE values dropped from 8.7 dB to 6.3 dB for the Kriging method and from 10 dB to 6.5 dB for the IDW p3 method.

In the literature on the topic several methods of interpolation are analyzed. Analyzing our results the smallest RMSE values were noticed for Kriging and IDW with the power of 3 or 4. For this reason these interpolation techniques should be recommended for REM construction.

Moreover, we also noticed the influence of the arrangement of sensors on the map quality, which seems to be important in the case of a network with a relatively small number of sensors deployed in a varied terrain. This problem is the subject of another research project conducted by our team.

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