Radio Environment Map to Support Frequency Allocation in Military Communications Systems

Marek Suchański, Paweł Kaniewski, Janusz Romanik, Edward Golan
Radiocommunications Department
Military Communications Institute
Warszawska 22A, Zegrze, Poland
{m.suchanski, p.kaniewski, j.romanik, e.golan,}@wil.waw.pl

Abstract—**This paper presents the concept of the Radio Environment Map (REM) to support Cognitive Networks and improve the efficiency of spectrum usage. The architecture of REM and its relation to other military systems are presented. The map construction techniques based on spatial statistics and transmitter location determination are discussed. The problem of REM quality and relevant metrics is analyzed. The results of field tests taken for UHF range with sensor network are discussed and exemplary maps with different interpolation algorithms are presented.**

Keywords-Cognitive radio, spectrum monitoring, frequency allocation,

I. INTRODUCTION

Common activities of NATO nations within the confines of coalition operations bring great amount of lessons learnt. In recent years they gave better understanding that the required high level of coalition communication systems interoperability cannot be achieved due to some fundamental technical shortages:

- Lack of common spectrum management system;
- Lack of common spectrum operation picture in the area of coalition forces interest;
- Inability to detect (in real time or quasi-real time) violations of frequency assignments, e.g. by vehicular jamming systems which can cause air force communications to be degraded or blocked;
- Lack of fast reaction procedures in case of frequency assignment violation.

Encountered problems pointed to the nations that it is of high relevance to take up the discussion and to make a NATO-coordinated effort to find solutions leading to spectrum management capability development, above the national level in particular. The area was organized into two domains:

- Frequency planning and allotment/assignment. More and more widespread awareness of the need to change static (sometimes manual) frequency assignment methods in favor of dynamic spectrum management led NATO IST Panel to the decision of creation of research task groups on Cognitive Radio in NATO and Cognitive Radio Networks. Their works focused on the safe and realistic plan of migration from legacy spectrum planning methods towards dynamic spectrum management and gradually to spectrum sharing [1,2].
- Spectrum monitoring and development of tools enabling fast response in emergency situations. NATO nations interest in working out standards and tools to create common spectrum operation picture and improvement of spectrum maneuver capabilities was confirmed in 2015 by establishment of the Exploratory Team (NATO IST ET-091) on Electromagnetic Environment Situational Awareness for NATO and consequently in 2017 by establishment of the Research Task Group (NATO IST-146 RTG-069).

The paper deals with the topics from the second domain described above. The central problem is creation of the radio environmental map (REM) which cooperates using standardized interfaces with sensor systems in order to refresh the spectrum map on the basis of the information how the frequencies are used at the specific time.

REM is a tool, which can be useful irrespective of the way in which the frequency assignment is performed. It means the progress in the first of abovementioned domains, though very welcome, does not influence the validity of working on REM. Frequency planning systems would benefit from the information on the real availability of frequencies and REM would supply communications managers with statistics of spectrum usage and each of coalition members would be able to take into account the needs and plans of the others, what would result in decreasing number of collisions on coalition level. Since it is not currently possible to monitor the whole spectrum of frequency in numerous locations at the same time, any action in response to a collision is taken usually after such an event was reported by the user. The primary users complain only about long-term or permanent difficulties, thus spectrum managers are unaware of great majority of events. Automation and making the system faster and more accurate would eliminate the feeling that there is no spectrum supervisor and would decrease the number of intentional violations of frequency assignments. To achieve the goal the monitoring system as minimum should enable identification of legal/illegal frequency users and their locations.

According to the NATO IST RTG-050 plan, REM is also needed to make a significant step towards coordinated spectrum management system in NATO [3].

The rest of the paper is organized as follows: the concept of REM architecture (Section II), map construction techniques (Section III), map quality (Section IV), the results of tests discussion (Section V), and conclusions (Section VI).

II. REM ARCHITECTURE

In most concepts REM is considered as a database which maintains complete and up-to-date information of the spectrum. This information may be composed of geographical features, available services, spectral regulations, locations and activities of radios, policies of the user and/or service providers, and experience gather from previous operations [7].

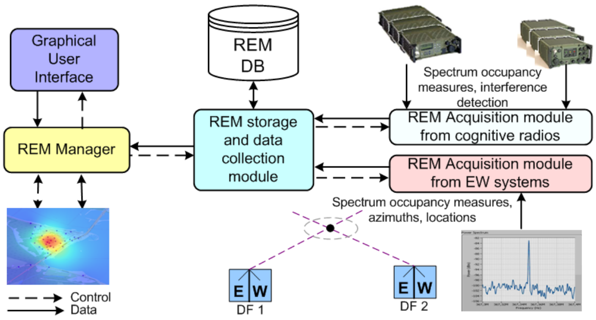

Figure 1. REM architecture to support tactical operation

The simplified architecture of REM excerpted from [5,6] and adapted to military applications was given on Fig. 1. REM architecture is comprised of the following modules: REM Manager, REM storage an data collection, REM Acquisition, sensors and GUI. REM Manager processes the data and controls the REM database in terms of measurement configuration, e.g., monitored 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 different specific sensors' systems. In the literature [4,7] sensors are generally named MCD (Measurement Capable Devices). MCDs are controlled through REM Acquisition modules and monitor spectrum. In civilian applications various devices with measurement capability may be used as MCDs, such as simple mobile phones, smart phones, notebooks, etc. When military systems are considered spectrum measurements may be taken by cognitive radios, Electronic Warfare (EW) systems, dedicated receivers or spectrum analyzers.

III. MAP CONSTRUCTION TECHNIQUES

The main goal of REMs is the support of frequency management systems resulting in more efficient frequency allocation. Therefore, REM must collect only consistent and reliable information on PUs activities and frequency occupation. This task seems to be challenging, since networks have dynamic nature in terms of the number of users and their activity, TX power, users' position, etc. For this reason REM must be updated in such a way that all crucial events are detected.

In the literature of the topic three main categories of the REM construction techniques are described, namely *direct*, *indirect* and *hybrid* [4]. *Direct* methods, called also *spatial statistics based methods*, are based on the interpolation of the measured data, while *indirect* methods, known also as *transmitter location based methods*, apply transmitter location and propagation model to obtain the estimated value. *Hybrid* methods combine both manners. *Direct* and *indirect* methods are described in more detail in the next subsections.

Spatial statistics based methods use measurement data taken at certain sensors' locations. It results from the fact that putting sensors in all required locations is impractical or simply unfeasible. Therefore, to get the data in missing areas different estimation techniques are applied with measured data as an input. The general assumption for the estimation process is that sensors closer to the requested location have higher impact than distant sensors.

The most promising estimation techniques described in the literature [4,7] are as follows: (1) Nearest neighbor method, (2) Inverse Distance Vector (IDW), (3) Kriging, and (4) Hybrid.

Nearest neighbor method, also named in the literature as proximal interpolation or point sampling, is one of the simplest interpolation methods, however it is also the least accurate. This method uses Theissen (or Voronoi) polygons. Polygons are defined by boundaries with equal distances from the points at which measurements were taken. A characteristic feature of these polygons is that their boundaries are exactly in the middle of the distance between neighboring points.

The interpolation of the unknown signal value P_1 at the given point (x_1, y_1) consists in assigning to this point the value of the closest measurement point P_0 at the location (x_0, y_0). In accordance with the above principle, all points located within a certain area will be assigned the same value. The advantage of the method is low complexity of the implementation and calculation, while the disadvantage is the step change in the signal value at the boundary of the polygon.

The Inverse Distance Weighting (IDW) method is based on the assumption that the signal value P_1 at a given point (x_1, y_1) is dependent on the values in the nearest measurement points. Samples taken at distant points have less impact on the estimated value.

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 close points have stronger impact. When the power p value is set to zero, regardless of the distance the weighting factors remain of the same level.

The unknown value at point (x, y) is calculated according to the following formula [10]

$$F(x,y)=\sum_{i=1}^{n} w_i f(x_i, y_i), \qquad (1)$$

where n is the number of sensors belonging to the circle with the centre at point (x, y) and radius R while $f(x_i, y_i)$ is the value measured at the *i-th* point.

The weighting factor w_i and the distance h_i (from the *i-th* point to the circle's centre) are calculated as follows

$$w_i = \left(\frac{1}{h_i}\right)^p \Bigg/ \sum_{i=1}^{n}\left(\frac{1}{h_i}\right)^p, \qquad (2)$$

$$h_i = \sqrt{(x-x_i)^2 + (y-y_i)^2}\,. \qquad (3)$$

Kriging belongs to the geostatic methods of interpolation. It means that it operates on stochastic basis, i.e. it takes into account the random variation of the interpolated feature. Interpolation is carried out on the basis of finding a statistical relationship between the values of the measured feature at known locations and the value at the interpolated location.

Kriging uses the relationship between the distance of the measurement points and the degree of their dependencies. This relationship can be presented in semivariograms [7], i.e., diagrams which are described by the set of parameters:

- semivariance (γ),
- still: the maximum value of the (γ),
- range: the distance at which the semivariogram reaches the maximum value and then remains on stable level,
- nugget: represents variability at distance values smaller than the typical distance between measurement points.

Mathematical functions that fit to the semivariogram are used to determine these parameters (Fig. 2). Semivariogram enables to find out the correlation for all pairs of points taking into account the distance between them.

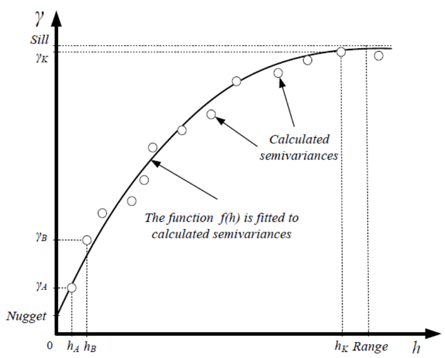

Figure 2. Exemplary variogram [7].

The performance of each presented method depends on the sensors (base points) deployment in terms of regularity and density as well as the exactness of measurements. However, according to the literature [4] the interpolation based on Kriging offers the highest estimation accuracy.

Methods based on spatial statistics enable to estimate the value of the feature (signal value in case of REM) without taking into account the direction of signal arrival or the location of the source of emission. Transmitter location based methods use the position of the transmitter with its parameters and applies propagation models to calculate the signal strength at requested location. The set of parameters describing a given transmitter can be composed of: TX power, antenna pattern, activity schedule. The quality of the estimation of the signal value depends strongly on the correct parameterization of the propagation environment [8].

The application of the method based on transmitter location seems to be challenging when mobile networks are considered.

IV. REM QUALITY METRICS

The main task of REM is the presentation of the electromagnetic environment. The quality of this presentation can be expressed by different metrics enabling to compare the estimated value with the real value.

In [9] authors proposed the Root Mean Square Error (RMSE) as a metric computed for all estimated locations within the analyzed area. The RMSE shows the dissimilarity in Received Signal Strength (RSS) between the estimated values and real values. The shortage of such approach results from the fact, that it is impossible to identify the reason, why the system could not take advantage of the spectrum opportunities [8]:

- when the RSS from PU was overestimated and the transmission from SU was restrained to avoid interferences,
- when the RSS from PU was underestimated, the transmission from SU was allowed and resulted in interferences.

To overcome the drawback of RMSE in [8] the Correct Detection Zone Ratio and False Alarm Zone Ratio were introduced. The area in which both the true and estimated REM indicates that the transmission is allowed is called Correct Detection Zone type-0. The area is called Correct Detection Zone type-1 if both the true and estimated REM shows that the spectrum is occupied. When on account of the inaccuracy of the estimation REM forbids the transmission, although it should be allowed, the area is named False Alarm Zone. The area in which the spectrum is occupied but REM allows transmission because of the estimation imprecision is called Missed Detection Zone. The presented in [8] Receiver Operating Characteristic curve (ROC curve) which shows the dependency between CDZ and FAZ confirmed that the location determination based methods has the higher performance when compared to Kriging or IDW based.

V. TESTS

To compare the complexity and the performance of the different REM construction techniques we conducted tests for UHF frequency range. First, measurements were taken in a real environment to get an input data, and then exemplary maps were created based on different construction techniques, namely Natural Neighbor, IDW and Kriging.

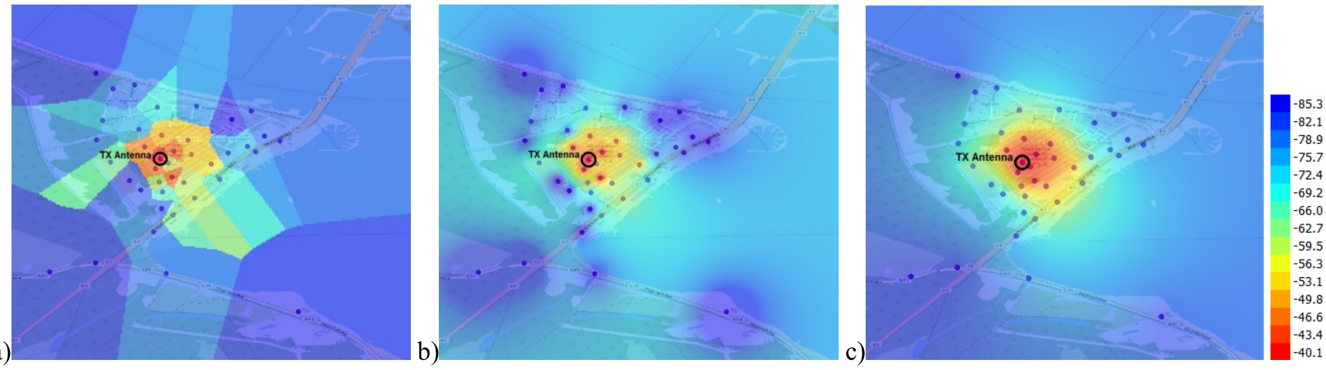

Figure 3. Constructed maps with different interpolation techniques (signal value in dBm): a) Nearest Neighbor, b) IDW with power 2, c) Kriging

The transmitting part of the system was composed of the signal generator connected to the control computer, the amplifier and the antenna mounted on the roof of the building at the height of 8 m. The receiving part consisted of the antenna installed on the vehicle, radio receiver and the computer controlling the receiver operation and recording measurements' results. The antenna was installed at the height of 3 m. The vehicle was moving within the preliminarily selected area. The following configuration of the testbed was used: (1) UHF frequency: 863 MHz, (2) modulation type: CW, (3) measured parameter: avg. RSS, (4) num. of averages: 10, (5) antenna type: omnidirectional. Tests were taken in the area of Zegrze in Poland.

The constructed maps with three interpolation techniques are presented on Fig. 3. The Nearest Neighbor method (Fig. 3.a) is computationally the simplest and creates polygons around each sensor. At the edges of polygons the signal strength changes rapidly. The position of the source of emission can be determined with little accuracy.

The IDW method (Fig. 3.b) is of moderate complexity and enables to estimate the signal strength quite well and the map is smoothed if sensors are deployed densely. When sensors are scattered the effect of bull-eye occurs and the size of eyes depends on the power used in interpolation process. Since one of sensors was set close to the transmitter, its location can be determined with quite good precision.

Kriging (Fig. 3.c) is computationally the most complex method of estimation. Within the whole area the signal value changes smoothly even when sensors are deployed sparely. Moreover, no effects like bull-eye is observed. The transmitter can be located with moderate accuracy.

VI. Conclusions

REM is considered as an essential element for cognitive radios support and a promising tool for better spectrum management in civilian and military systems.

In this paper three methods for signal strength interpolation were presented and maps constructed with different techniques were discussed with emphasis of their performance and implementation complexity. The method selected for REM should estimate the signal strength with required precision at any location and determine position of the transmitter with requested precision. IDW and Kriging seem to be promising however the complexity of Kriging is much higher. Computational power of devices used for REM implementation should be taken into account, especially when small scale dynamic military operation is considered.

Research works in the area of spectrum monitoring and efficient frequency allocation became more intensive which allows to expect significant advances in the near future.

References

[1] M. Suchanski, P. Gajewski, J. Lopatka, P. Kaniewski, R. Matyszkiel, and M. Kustra, "Coordinated Dynamic Spectrum Management in Legacy Military Communication Systems", Wireless Innovation Forum European Conference WinnComm-Europe 2016, 11-12 October 2016, Paris, France.

[2] B. Scheers, "Introduction of Dynamic Spectrum Access technology in NATO Europe tactical communications", 2013 IEEE Military Communications Conference, DOI 10.1109/MILCOM.2013.131.

[3] M. Suchanski, R. Matyszkiel, P. Kaniewski, M. Kustra, P. Gajewski, and J. Lopatka, "Dynamic Spectrum Management as an Anti-Interference Method", Proceedings of SPIE Vol. 10418 (SPIE, Bellingham, WA, 2017), 2269288, ISSN: 0277-786X, ISSN: 1996-756X (electronic), DOI 10.1117/12.2269294, April 20, 2017.

[4] H. B. Yilmaz, T. Tugcu, F. Alagöz, and S. Bayhan, "Radio Environment Map as Enabler for Practical Cognitive Radio Networks" in IEEE Communications Magazine, 2016 International Conference on, May 2016, pp.162-169.

[5] Flexible and Spectrum Aware Radio Access through Measurements and Modeling in Cognitive Radio Systems, FARAMIR project, Document Number D2.4, Final System Architecture.

[6] T.Cai, Jaap van der Beek et. al., "Design of Layered Radio Environment Maps for RAN Optimization in Heterogenous LTE systems", UEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications, 2011, pp. 172-176.

[7] M. Pesko, T. Javornik, A. Košir, M. Štular, and M. Mohorčič, "Radio environment maps: The survey of construction methods", KSII Transactions on Internet and Information Systems, vol. 8, NO. 11, December 2014, http://dx.doi.org/10.3837/tiis.2014.11.008

[8] B. H. Yilmaz and T. Tugcu, "Location Estimation-based Radio Environment Map Constructing Techniques in Fading Channels", Wireless Communications and Mobile Computing, 2015, pp. 561-70.

[9] S. Ureten, A. Yongacoglu, and E. Petriu, "A comparison of Interference Cartography Generation Techniques in Cognitive Radio Networks", IEEE International Conference on Communications, 2012, pp. 1879-83.

[10] D. Denkovski, V. Atanasovski, L. Gavrilovska, J. Riihijärvi, and P. Mähönen, "Reliability of a Radio Environment Map: Case of Spatial Interpolation Techniques," in Proc. of 7th CROWNCOM, pp. 248-253, June 18-20, 2012.