Electromagnetic Environment Situational Awareness

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***Abstract*—Military radio, EW and RF sensor systems operate in a congested and contested electromagnetic environment. The NATO Science and Technology Organization established the Research Task Group 069 in order to take charge of the IST-146 project on Electromagnetic Environment Situational Awareness. The project was aimed at evaluating the operational benefits for NATO in line with the Electromagnetic Spectrum Strategy and at evaluating the Radio Environmental Map (REM) technology. The paper describes the military scenario considered for the study. Its operational analysis establishes the importance of Electromagnetic Spectrum Command and Control integrated with other C2 processes. The description of the data sources, models, and representation is done. Key user benefits are highlighted. Then proposals for possible evolution of electromagnetic operations and spectrum management within NATO are made. The paper further describes the proposed reference architecture based on the Internet of Things (IoT). It establishes how the relationships between the REM elements have been validated through the project scenario. Tests and simulations, carried out for the construction of measurement-based REMs and transmitter localization, are presented. The paper finally describes the proposed demonstration, which enables understanding through visualization of an interference situation and de-confliction by dynamically re-assigning frequencies.**

Keywords—Electromagnetic Environment, Situational Awareness, Radio Environment Map, Spectrum Management

I. INTRODUCTION

A. Electromagnetic Environment Situational Awareness

Electromagnetic Environment Situational Awareness (EME SA), under the name of Radio Environmental Map (REM) [1], has attracted a lot of attention in the wireless communications and electronic warfare research communities. It can be seen as a field of application for Big Data Analytics to enhance the Spectrum Awareness on the battlefield.

The REM consists of a space-time-frequency database and a tool suite that can store and process the relevant information and derive a representation of the Electromagnetic Environment (EME) for Electromagnetic Operation situation awareness. The space-time-frequency database consists of information, such as monitoring information, geographical features which characterise the terrain (and therefore the propagation), the available EM assets along with their activities, spectral regulations, locations, and relevant policies etc. EM assets include all emitters and recievers in the battlespace, intentional, unintentional, civil, blue or red.

B. Military relevance

Management and access to the Electromagnetic Spectrum (EMS) are critical to achieveing information superiority in military operations. The REM provides an enhanced capability to report to the military commander on situational awareness of spectrum in time, space, and frequency. As a possible contributor to the NATO Electromagnetic Spectrum Strategy [2], it is an enabler for Command and Control (C2) of spectrum, dynamic spectrum management, Electronic Warfare (EW) support for Common Electronic Order of Battle (C-EOB), and transmitter localisation. It facilitates the optimisation of spectrum usage in order to improve operational effectiveness by enabling dynamic management, coordination, and synchronisation of spectrum usage. Such coordination may encompass several area of responsibilities and as such is critical during NATO coalition operations.

C. Research task group

The NATO Science and Technology Organization established the Research Task Group 069 (RTG-069) in order to take charge of the IST-146 project on EME SA for three years. The RTG completed its work in november 2020. The project aim was too evaluate the operational benefits of implementing an EME SA/REM capability for NATO. The project included several work packages (WP) related to scenario and operational analysis (WP1), architecture including test and simulation (WP2), and demonstration

(WP3). The objective of the RTG was to propose an improvement roadmap for C2 of spectrum and dynamic spectrum management based on REM capabilities. The military functions that were addressed included transmitter localisation and transmit power estimation, elimination of interference and jamming on the battlefield, within and between allied force elements during operations, and provide support for real time establishment of the Electronic Order of Battle. Proposals for future evolution of the NATO spectrum management in operations [3] utilising REM have been developed.

II. WP1-SCENARIOS AND OPERATIONAL ANALYSIS

A. *Introduction*

The use of the EMS permeates all military operations and underpins successful use of the majority of military capabilities. It is also a limited resource and as such must be managed for effective use and access to be maintained. Decisions on how best to use the EMS must be aligned with operational priorities, spectrum availability and electromagnetic (EM) threat. In a military context, the EMS requires a C2 process, integrated with other C2 processes, that operates at all levels of the military hierarchy. In common with all military C2 processes, spectrum C2 decisions need to be made based on knowledge of the EM environment to which the decision pertains. This knowledge is referred to in this project as Electromagnetic Environment Situational Awareness (EME SA).

The knowledge of the state of the EMS needs to be presented to appropriate staff in a form which is useful, relevant and able to support a range of different tasks. WP1 of this project explored the C2 and spectrum management processes that require EME SA to better understand the need, the means of provision and the operational benefits that may be realised. This will provide a basis for development of an architecture to provide EME SA based on radio map technology and for some initial demonstrations of what can be achieved.

B. *Requirements*

The key requirements for EME SA are: what information is pertinent to different Electromagnetic Operations (EMO) and Battlespace Spectrum Management (BSM) tasking, how this information presented to the user, and what sources of data are used to compile these information products. The information and information attributes that a user requires vary significantly depending on the task being performed and WP1 is exploring this aspect of EME SA.

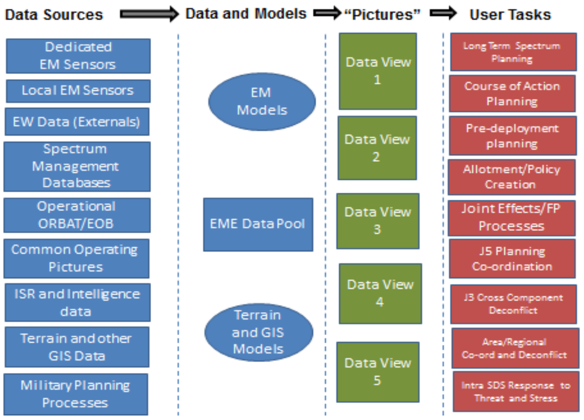

Fig. 1. General structure of EME SA/REM Data Sources

The general structure of an EME SA system is illustrated in Fig. 1. This structure shows potential data sources that could be used to compile the data pool and provide the input data for models used to generate "pictures" for use by military staff to perform EM C2 and BSM Tasks.

C. *Data Sources*

The data required to generate EME SA pictures needs to be drawn from a wide variety of sources. The data will need to describe the EMS showing the locations, frequencies, and times of operation of emitters and receivers of the coalition, civil users and the adversary. The fidelity of the data required to compile an EM picture will vary widely. The tactical de-confliction of two coalition force elements, as they move towards each other in the battlespace, requires details of the frequency assignments, locations, and expected movement at timescales relative to their rate of movement. At the other end of the scale, understanding the long term spectrum needs of the coalition to support regulatory processes needs a broad picture of evolving spectrum use.

In Fig. 1, the following classes of data source are identified:

Dedicated EM Sensors: These are dedicated sensors whose prime function is to gather spectrum usage data in a specific area or on a specific route. They could be deployed to areas with a high density of spectrum use or to areas that are operationally critical.

Local EM Sensors: They are sensors that are incorporated into spectrum dependant systems (SDS) that will gather spectrum usage information in the local area. Generally, these sensors will be limited to the bands used by that SDS in which they are hosted. In future the sensing function may be built into the system waveform and will be used to drive Dynamic Spectrum Access (DSA) systems.

EW Data: Collection of RF externals data is an inherent function of Electronic Surveillance systems. The data collected, specifically the frequencies, locations and some limited identification data (subject to classification), has the potential to make a significant contribution to EME SA. Collection and dissemination of data to an EME SA capability could be a secondary function of an EW capability so as not to undermine primary tasking. Contribution of data to EME SA could be a secondary use for data already being collected or the collection of data while moving through the battlespace to reach an operational target or area. In critical areas or at critical moments, it may become a primary function.

Spectrum Management Databases: These databases contain the assigned frequencies and other data pertaining to the radio systems deployed into the battlespace including the identity of the platforms the SDS is fitted to. The spectrum management (SM) databases should also include the locations and assignments of key civil SDS. Regulatory data is also available.

Operational Order of Battle (ORBAT): The operational ORBAT contains information on all military force elements deployed into the battlespace. Used with the spectrum management databases, the SDS associated with each force element can be determined. The ORBAT must contain all force elements and include those with communications, RF sensing and EW equipment.

Common Operating Pictures: Common operating pictures show the locations of military forces elements in real time and potentially historically, which together with the SM database provides the locations and spectrum assignments for coalition forces.

ISR and Intelligence Data: This data helps to locate and characterise hostile SDS.

Terrain and other GIS Data: This data enables coverage of SDS and the likelihood of interference to be calculated using EM Models. Weather and space weather data is included in the GIS data set.

Military Planning Data: This data has the potential for spectrum clashes to be forecasted and thus pre-empted.

D. Data and Models

It is proposed that the data, which is available and collected pertaining to EMS usage, could be stored or accessible to what has been described as an EME data pool. This would be a flexible store where a variety of data types and in part unstructured data could be stored. This type of data store is required due to the variations in data stored and with many data sources being partial and likely to be incomplete. It is thought that this data would then be fused in various ways depending on the EME picture required.

Models of the terrain and other Geographic Information System (GIS) information are important to understand how emitters and receivers in the battlespace will interact and would be used in EM propagation models. Calculating coverage and the impact of interference are examples of how terrain and EM models will be used.

E. "Pictures"

A "picture" is used here as a generic term for the formatting and representation of datasets that are presented to users. In some cases, e.g. automated spectrum management processes, there may not be any form of visualisation but in many cases there will. Data sets are created based on extracts from the EME data pool based on combinations of frequency ranges, time ranges and areas of interest. These data selections are then processed or fused to produce a data product suitable for a user task being performed.

Examples of the picture variants that could be produced include:

- **Radio Environment Maps:** Showing a snapshot in time of spectrum users in an area of interest with a specific frequency range.
- **Heat maps:** Showing spectrum occupancy over a limited range of frequencies in a grid of locations over some defined time.
- **Coverage Maps:** Showing the geographical coverage of an emitter or emitters.
- **Waterfalls:** Showing spectrum usage of a frequency or channel range over a time period of interest.

F. User Tasks

There is a wide range of EMO and BSM tasks that would benefit from EM situational awareness products. Some of these are identified in Fig. 1. In addition to these, there is a range of routine BSM tasks that could be performed much more easily or much more accurately, if timelier and better quality information was available. Examples include: a) less risk adverse spectrum allotment and frequency assignment; b) identification of unused, allocated or assigned spectrum; c) improved spatial and temporal spectrum reuse; d) pre-emption of coalition spectrum conflict; e) improved synchronisation and co-ordination of spectrum use in operational planning; f) faster and improved resolution of interference; g) better response to EM threat; h) enabling more agile/dynamic use and operation of Joint Restricted Frequency List (JRFL).

G. Scenarios and vignettes

In this project, we considered a range of coalition operational scenarios including NATO article 5 conflict or de-escalation, counter-insurgency (COIN) operations and humanitarian operations. The main differences between these scenarios are the presence of adversary EM activity and capability, concern over interference with civil systems, use of EW by both sides and interoperability with local and non-NATO forces. To cover these different operation types and needs, we identified 12 vignettes that cover many aspects of the use of an EME SA capability (see TABLE 1).

TABLE I. DESCRIPTION OF 12 VIGNETTES

No.	Description
1	Assignment and allotment of limited frequencies to military units (During Operation) Including Nation/coalition co-ordination.
2	Deconfliction of own force jammer.
3	Producing and updating policy/rules for DSA.
4	Tasking a UAS Mission, Convoys or Manned Air Platform requiring change of frequencies.
5	Planning frequency allotments and assignments pre-operation.
6	Interference/Jamming Investigation (Diagnosis of spectrum problem).
7	Counter ISR Threat spectrum planning and response.
8	Deconfliction of own force ELINT/SIGINT operation.
9	Threat protection of a complex/networked weapon operation.
10	Understanding the impact of regulatory change.
11	Understanding the civilian context of an operation.
12	Improved spectrum sharing.

A small selection of these will be demonstrated at a basic level in the field using carefully constructed trials sequences. However, field demonstration of the use of EME SA capability in all these vignettes was beyond the scope of this project; so the conceptual demonstration of most has been done by analysis and inference to the functional elements of the field demonstrations.

The outputs of these demonstrations and analyses provide an understanding of and outlinine the benefits of EME SA.

H. Benefits

The key benefits of an EME SA capability have been identified and use of EME SA was evaluated for use in EMO and BSM processes against a series of metrics. The key benefits we evaluated were: a) effort needed to fit users into a given spectrum allotment; b) efficiency of spectrum use in time, space, and frequency; c) identify unused spectrum either assigned, allotted or unused more generally in a geographical area and at specific times; d) speed of problem resolution; e) stability of spectrum plan versus changes with DSA; f) resilience of spectrum plan and assignments; g) speed to ascertain operational spectrum need; h) speed to adjust assignments; i) operational performance (time to success, casualties, costs); j) speed to plan missions and to coordinate/synchronise spectrum use; k) effectiveness of the response to a threat; l) improved communications (and other EM User) capability.

I. Possible evolution of electromagnetic operations and spectrum management

EMO: Electromagnetic operations (EMO) are defined as synchronized activities associated with spectrum management, signals intelligence (SIGINT), electronic warfare (EW), communications, and navigation warfare, among others. As part of EMO, mastering the electromagnetic spectrum (EMS) is key for operational superiority. To that extent, the EME SA/REM capability is seen as of major importance in enhancing spectrum management capability in the battlespace.

Command and control: At the level of command and control (C2) operations, the EME SA/REM, in the form of a C2 of spectrum (EMS C2), may be able to provide overall/aggregated information on the effective spectrum usage, thanks to information coming from existing frequency management cells on the battlefield. Such information, fused with other sources of non-spectral information (regulation, weather, order of battle, etc.) can contribute to the C2 process.

Command and control during joint operations may then involve several electromagnetic capabilities, such as C2 of EW [4] and EMS C2, Fig. 2.

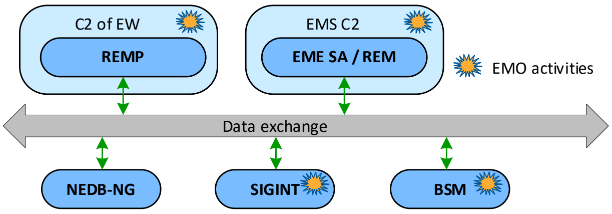

Fig. 2. EME SA/REM within command and control organisation

The NATO Common Electronic Order of Battle (C-EOB) exchange format is seen as a possible format for overall data exchange.

Battlespace data repository: it involves various existing or planned databases (e.g., Battlespace spectrum management (BSM), NATO emitter database (NEDB, NEDB-NG), NATO Recognized Electromagnetic Picture (REMP)).

The EME SA/REM database contributes to this data organization. As a first step of the EME SA/REM implementation roadmap, the EME SA/REM acts as an extra base providing complementary information. If the various organisations in charge of their administrations deem it necessary, a more integrated solution may be considered in further steps.

As an example, the NEDB-NG data can be used to feed the EME SA/REM with nature and characteristics of emitters. Alternatively, the EME SA/REM – offering new awareness and decisional capabilities – can contribute to the protection of frequency lists of major importance for the operation, thanks to interaction with the BSM. In addition, the EME SA/REM can provide localisation and identification information to be crosschecked with those of the C2 of EW. The identification of civilian and blue forces emitter by the EME SA/REM can facilitate the identification of the red forces emitters.

The way the data is selected in relation to the need will require an appropriate fusion and distribution topology (e.g. summarising data up the operational hierarchy and increasing granularity as on moves towards the tactical space). The benefits of implementing EME SA should also be weighed against the increase of communication capacity if any.

Spectrum management and SM in Operations: The ASP-01 [3] provides procedures, instructions, guidance, and technical information concerning radio frequency spectrum management by NATO. It is designed to optimise the use of the available radio-frequency spectrum by friendly forces in order to achieve information superiority.

Most of ASP-01 spectrum management activities may be facilitated by use of the EME SA/REM capability. It is not anticipated a one-step revision of the ASP-01, but more pragmatically a step approach to ensure that one step is proven to be efficient before entering a new one. The possible evolutions are mainly:

- Elaboration of the initial state/map of the EME on the battlefield.
- Identification of unused radio frequencies. The EME SA/REM containing spectrum monitoring data, can inform on used frequencies at a given time, and one can deduce the frequencies that may be available for new assignments.
- Enhancement of coordination and way to dynamic spectrum management. One can anticipate that the implementation of the EME SA/REM capability (or a subset of), once disseminated at various level of the command chain, could contribute to streamline the exchange of information and thus render possible the dynamic spectrum management. The EME SA/REM also being capable of managing policies of dynamic spectrum access radio, can contribute to an overall way to dynamic spectrum management.
- Streamlining of frequency coordination during operations and exercises and of Civil Military co-operation (CIMIC).
- Interaction with BSM database.
- Contribution to interference resolution. The EME SA/REM can implement or record transmitter localisation, which is one of the key information in the process of solving interference situations. The above position can evolve during the operation. One of the interests of the EME SA/REM is to allow tracking successive positions of this transmitter to enhance interference resolution. The EME SA/REM provides the effective use of the spectrum in a given area (frequency, time, location).
- Protection of other radio equipment. The EME SA/REM contains both transmitter and receiver characteristics and locations, not only for blue forces but also for civil equipment thanks to information extracted from civil SM databases. With this information, the REM can facilitate protection of civil equipment if needed. It may be of particular interest during peacekeeping operation or exercise.

III. WP2-ARCHITECTURE

The REM fundamentally provides a framework to interconnect a set of devices (to include, but not limited to databases, standards, policies, sensors, as well as geographic and metrology data) for the purpose of exchanging information critical to decision support for users of the REM. Our definition of the REM is consistent with a more general description of the Internet of Things (IoT). A similar concept to IoT is the Industrial Internet of Things (IIoT) for which the Industrial Internet Consortium has matured a reference architecture. IIoT is more applicable to data acquisition for the purposes of feedback and control versus for the purposes of information generation for decision support. So without loss of generality, a IoT reference architecture is used as a starting point for the REM.

A reference architecture provides standardization and a common terminology that can be used to develop specific architectures as solutions to unique domain problems like the REM. There are several initiatives worldwide to develop a reference architecture for the IoT [5]. The RTG chose to utilize a reference architecture developed by the European FP7 Research Project IoT-A from Sep. 2010 – Nov. 2013 [6] titled "Internet of Things – Architecture, Deliverable D1.5, Final architectural reference model for the IoT v3.0". The NATO Architecture Framework (NAF) methodology was considered, to the maximum extent possible, in the definition of the REM application architecture. Therefore, our project enables future efforts to create a fully NAF confomant REM architecture.

A. Reference Architecture

Our objectives in using the IoT-A reference architecture for defining the REM framework are to develop a REM Electromagnetic Spectrum domain specific architecture with the following attributes: a) scalability to meet current and new requirements; b) enable communication between heterogeneous devices; c) manageability of existing and new devices; d) governance under current NATO frameworks; e) privacy within coalition nation information systems; f) security including cyber hardening; g) portability within different IT infrastructures; h) interoperability between coalition partners; i) rapid deployment; j) operation under wired and wireless connections.

These attributes lead to an adaptation of the IoT-A specifically for REM, which identifies the relationships between the REM, REM Users, REM Things, and REM devices. It is depicted in Fig. 3.

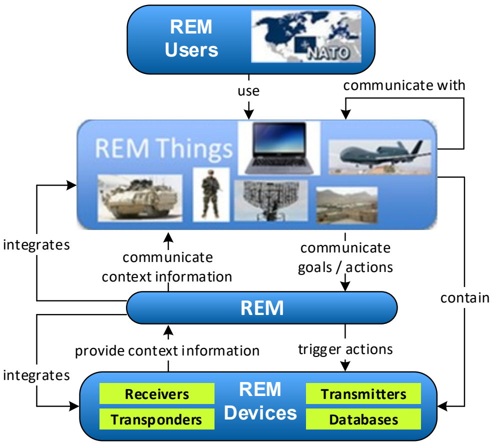

Fig. 3. Relationships of REM components

The definition of a REM Thing is an object in an area of operations that interacts with the REM environment. A thing can be a platform (vehicle, dismounted soldier), radio, radar, or electronic warfare equipment or even a complete building or base.

The definition of a REM Device is a radio frequency receiver, transmitter, or transceiver, which can collect information directly about the EM environment. REM Devices also include databases, standards, policies, non-EM sensors, as well as geographic and meteorology data.

Usually, the device is part of a thing. The thing processes the devices' context information and communicates selected information to other things. Furthermore, the thing can pass actions to transmitters. Things are directly or indirectly used by the REM Users.

The definition of a REM has already been given in section I.A. The reference architecture model for the REM from the IoT-A appears in Fig. 4.

The IoT-A reference architecture consists of six layers with two additional layers, management, and security that interact with all other layers.

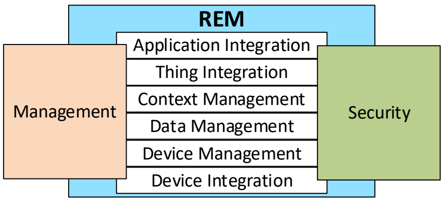

Fig. 4. IoT-A reference architecture used for REM

B. Architecture Process

The process to turn the IoT-A reference architecture into a specific architecture for the REM unique to the Electromagnetic Spectrum domain involves defining the interfaces between the layers of the architectural model, defining the functional blocks within each layer, and deciding on which interfaces and functions will be standardized. An example of the detail generated for the Device Integration layer appears in Fig. 5.

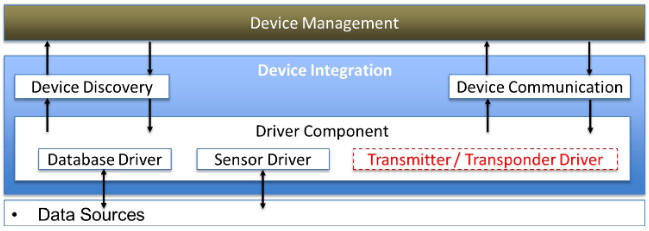

Fig. 5. Detailed example of device integration layer for REM

As part of the architectural process, we defined data categories with respect to how often the particular form of data is updated: a) Real Time [updated every < 1sec]; b) Near Real Time [updated every < 1min]; c) Static [updates on order of hours/days/weeks].

Although we architect the REM to collect real time and near real time data from devices, the focus of our project is on static device data collection to provide static context information in the form of a REM database entry. The focus on static information for decision support is consistent with a C-EOB exchange format. Future extension of the REM to real time data and/or automated command and control may require a different exchange format such as Joint Consultation, Command and Control Information Exchange Data Model (JC3IEDM).

C. *Architecture Validation*

Architecture validation is the process by which one ensures the architecture meets the needs of the user and other stakeholders. The methodology used to validate the specific IoT architecture for the REM is an extension of a context toolkit for the IoT [7], where the proposed REM architecture is validated to support the required user action(s) relative to the goal(s) and context information of an operational vignette, see connections in/out of REM in Fig. 3.

As an example, we provide the detailed results of validation of the REM architecture with Vignette 4: Tasking a UAS Mission, Convoys or Manned Air Platform requiring change of frequencies (see section II.G). Validation of the REM specific IoT architecture for the other vignettes proceeds in the same fashion.

We first start with the situation, stakeholders, and thing(s) for Vignette 4:

- Situation: Two-country coalition for humanitarian assistance, Country A supporting host Country B, Country A providing reconnaissance with unmanned aerial system (UAS).
- Primary stakeholders: Joint Coalition Spectrum Manager.
- Other stakeholders: Country A – Force Element, Country B – Spectrum Manager, SIGINT Electronic Warfare Operations Cell (SEWOC), Electronic Warfare Coordination Center (EWCC), Electromagnetic Battle Manager (EBM).
- Primary Thing: UAS.
- Other Things: Country A/B radars, vehicles, other platforms, civilian cellular tower (e.g. 4G/5G).

With the situation, stakeholders and thing(s) established, we then identify the goal(s) and required action(s):

- Goal; Identify interference free communications settings for command and control (C2) and data for UAS.
- Action; Inform Country A – Force Element of communications settings.

Finally, we identify the relevant REM context information required for support of the Vignette: a) spectrum occupancy including adjacent bands; b) policies and regulations applicable to UAV mission; c) weather conditions including prediction; d) thing (UAS) Common Operating Picture (COP), flight plan; e) aggregation and visualization of device context information; f) recommendations for C2 and data communications settings; g) risk profile for C2 and data communications probability of interference.

With this information, the validation process proceeds to walk through the specific REM architecture components. Interfaces, functional blocks, and standards are used to determine if the REM architecture is capable of providing the context information to the correct stakeholders at the right time and place and whether it can support user/stakeholder decision processes to drive the intended action(s) with the result of achieving the Vignette operational goal(s). Our application of this process to all 12 Vignettes (TABLE 1) successfully validated the REM architecture.

IV. TESTS AND SIMULATIONS

This section shows tests and simulations conducted during the project period.

A. *Electromagnetic Situational Awareness supported by Measurement-based Radio Environment Maps*

In this section we discuss the problem of measurement-based maps construction and the correctness of the signal level estimation. We present exemplary maps created with different interpolation methods with the aim to analyse how the number of sensors and their deployment affect the quality of the maps.

In our research work, we focused on direct methods. Direct methods use measurement data taken from sensors only at certain locations [8]. 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. In the literature [8][9] the following estimation techniques are described as the most promising: (1) Nearest Neighbour (NN), (2) Inverse Distance Vector (IDW), and (3) Kriging.

To investigate the impact of the number of sensors and their arrangement on the map quality, field tests were done for selected frequencies in the UHF band with one transmitter (at the frequency of 1997 MHz). The sensor network that measured the received signal level was composed of 39 sensors, irregularly arranged within the area of 4 km^2. It is worth noting that the sensors were arranged irregularly due to the fact that the measurements were taken in a real environment. The detailed configuration of the measurement system and the terrain characteristics were presented in [10].

The results of measurements were used as an input data to create maps with selected interpolation methods. Exemplary maps were created for various number of sensors and for different arrangements of sensors. Finally, the RMSE values were calculated [10], and the quality of maps was assessed.

In the first part of our research work, the attention was paid to the influence of the density of the sensor network on the REM quality [10]. Results of the tests were analysed 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 created.

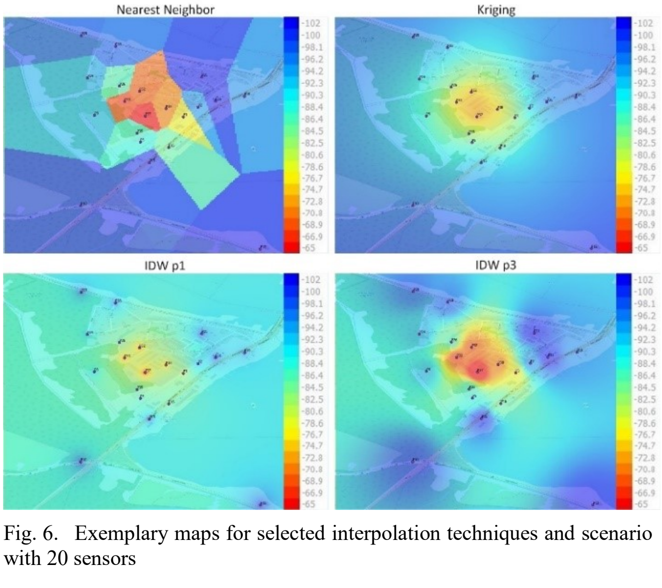

Fig. 6. Exemplary maps for selected interpolation techniques and scenario with 20 sensors

The NN method (Fig. 6, upper left image) uses polygons that are created around each sensor. The number of neighbouring sensors and their deployment determines the size and the shape of the polygons. Within each polygon, the signal strength takes the value measured by the sensor. The drawback of the method results from the fact that the signal strength changes abruptly at the edges of the polygons, e.g. between the dark orange polygon in the centre and the blue one visible on the top of the map. When the Kriging method is employed (Fig. 6, upper right image), the signal value changes smoothly within the whole map. Our analysis confirmed that there are no rapid changes in the signal value, even if the sensors are deployed sparsely or unevenly. The IDW method (Fig. 6, lower row images) creates smoother maps in contrast to NN. The disadvantage of this method is the bull's-eye effect. It is clearly visible that the size of the bull's-eye depends on the power p used in the interpolation process (smaller eyes for IDW p1 than for IDW p3). We found out that the estimation of the signal strength is quite precise when the power p is set at 3 or higher and the sensor network is quite dense.

To assess the quality of maps, we compared measured and estimated values, and finally we calculated the Root Square Mean Error (RMSE). The average values of RMSE for each scenario are shown in Fig. 7. The drop in the RMSE for an increasing number of sensors may be easily noticed for Kriging and IDW with power p higher than 1 interpolation technique. For the IDW p1 method, the differences between average RMSE values are inconsiderable. When NN method was applied, surprisingly the smallest RMSE value occurred for the scenario with 20 sensors (approx. 9 dB), while for the scenario with 26 sensors the RMSE reached 10 dB.

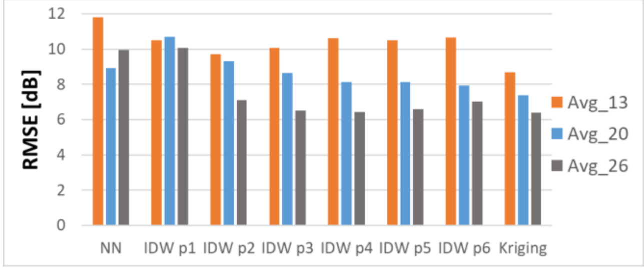

Fig. 7. Average RMSE (in dB) for the network with 13, 20 and 26 sensors

In general, the increase in the number of sensors from 13 to 26 caused a noticeable improvement in the quality of REM maps. The average RMSE values decreased: 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 second part of our research work, we focused on the impact of the deployment of sensors on the REM quality. The results were presented and discussed in [11]. We found out that in some cases even a small rearrangement of the sensors was beneficial, e.g. when we replaced two selected sensors by the other two located in different positions the RMSE decreased by up to 2 dB for Kriging and IDW p3.

Our main conclusion in this section is that the smallest RMSE values were noticed for Kriging and IDW with the power of 3 or 4 and that these interpolation techniques should be recommended for REM construction. In general, placing more sensors in the network makes the quality of REM higher since the RMSE drops significantly. If the number of sensors in the network is limited (for instance, in small tactical operations), attention should be paid to the optimum deployment of sensors. The stratified approach seems to be the most promising deployment algorithm.

A wider dicussion of results and conclusions were given in [10] and [11].

B. *Effect of Log-Normal Shadowing on RSS-based Single and Multiple Transmitter Localization for Radio Environment Map*

The problem of transmitter localization is an important problem in a tactical context. A method for single and multiple jammer localization using only received signal strength (RSS) from spectrum sensing devices for radio environment maps (REM) has been developed during this project [12]. The effect of log-normal shadowing has also been studied [13], modelled as a normal distribution variable X with zero mean and standard deviation σ dB $(X \sim N(0, \sigma^2))$. Note that typical values of shadowing are between 4 and 13 dB.

Monte Carlo simulations (random position and power of the unknown transmitter with shadowing) have been performed for comparison between different algorithms 1DLS [12], 1DWLS [13], ChanLS, and ChanWLS [14] with 16 equidistant spectrum sensing devices in an area of 1 km^2.

Fig. 8 shows the percentage of convergence, the mean and standard deviation of the estimated path loss exponent, distance, power versus the standard deviation σ dB. One can see from these results that a log-normal shadowing effect of 10 dB will not give valid path loss exponents or power estimates, but still can provide about 10% error of distance of the area considered, meaning that log-normal shadowing has a quite signifactive negative impact on the estimates. For low values of shadowing, the ChanWLS has the best performance for localization. For moderate values of shadowing, the ChanWLS and 1DWLS have the best performance for localization. For high values of shadowing, the ChanLS and 1DLS have the best performance for localization.

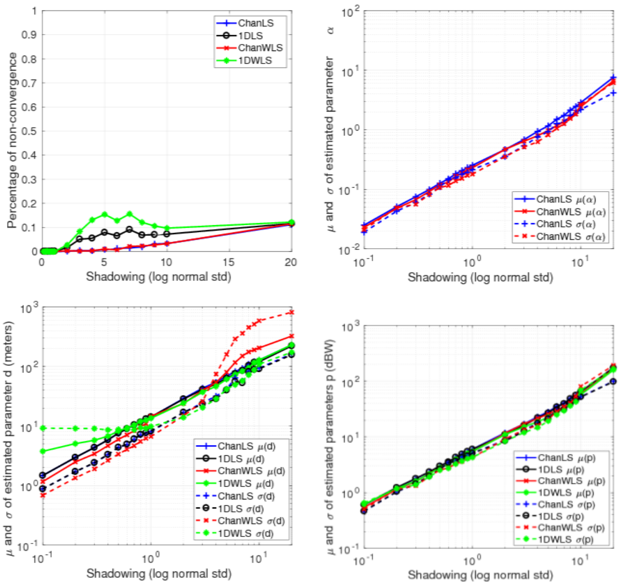

Fig. 8. Effect of Log-Normal Shadowing on the convergence and estimation of parameters

The same algorithms have been applied to the real data provided by [15] for transmitter localization and transmit power estimation. The results are shown on Fig. 9.a, giving a distance error (meters) with the different algorithms

ChanLS=255.9, 1DLS=231.4, 1DWLS=41.1, ChanWLS=85.5.

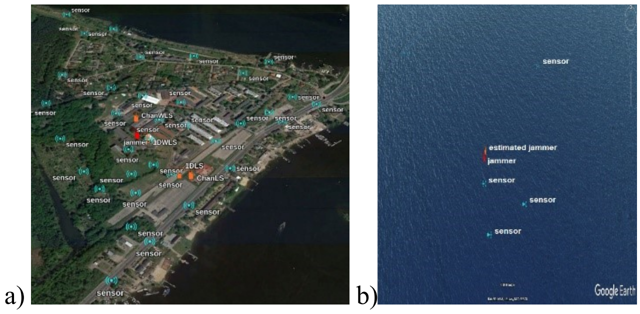

Fig. 9. Application of algorithms on: a) real data [14], b) EMANE tools

The distance errors are due to two factors: (a) terrain is non-homogeneous in terms of path loss exponent; (b) log-normal shadowing has too much impact on the path loss exponent and power parameters.

We have also combined the REM algorithms and EMANE tools for transmitter localization and transmit power estimation in a free space path loss channel model as shown in Fig. 9.b. In this case, all the nodes are in Line of Sight (LOS), therefore the log-normal shadowing effect is minimal. The difference between the position of the estimated transmitter and the true position of the transmitter is due to our 2D model, which does not take into account the altitude.

Therefore, it can be concluded that for transmitter localization and transmit power estimation, these kinds of techniques work well with low log-normal shadowing values (e.g., in LOS).

V. WP3-DEMONSTRATION

Under the project, we sought to run a demonstration of EM Situational Awareness and C2 of Spectrum, based on Vignette 1 defined in section II.G. The demonstration would also have partially demonstrated the efficacy of using EME SA in the other vignettes defined in II.G as much of the functionality is common between vignettes. Unfortunately, due to the COVID-19 constraints, this demonstration has proved unachievable during the time period of IST 146. The scenario would have been as follows:

Two dismounted co-located patrols are initially assigned the same frequency set for their Digital Mobile Radio (DMR) Personal Role Radios (PRR). Upon one of the dismounted patrols reaching a ridgeline (which previously allowed both patrols to re-use the same frequency as neither network could cause interference that propagated to the other), the DMR PRR networks now come into interference. A control station is able to understand and see this conflict via the use of an EME SA/REM. The control station is now able to de-conflict both patrols and dynamically re-assign frequencies via a clear channel (in this case a MANET network). This demonstrates C2 of Spectrum via the use of EM Situational Awareness.

The following equipment setup was foreseen to be implemented during the demonstration: a) 2x DMR PRR Networks operating at 446.14375 MHz initially; b) 3x Spectrum Sense nodes (ETTUS Software Defined Radios); c) 5x MANET nodes (3 at Spectrum sense locations, 2 with dismount); d) 1x EME SA/REM fusion node (RADIO MAP).

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