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Characterization of Complex Electromagnetic Environment Created by Multiple Sources of Electromagnetic Radiation

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Abstract**—**This paper considers the characterization of a complex electromagnetic environment due to multiple sources of electromagnetic radiation as a five-dimensional surface which can be described by a set of several surface sections including: instant EM field intensity distribution maps at a given frequency and altitude, instantaneous spectrum at a given location in space and the time evolution of the electromagnetic field spectrum at a given point in space. This characterization if done over time can enable the exposure levels of Radio Frequency Radiation at every point in the analysis area to be determined and results interpreted based on comparison of the determined RFR exposure level with the safe guidelines for general public exposure given by recognized body such as the International commission on non-ionizing radiation protection (ICNIRP), Institute of Electrical and Electronic Engineers (IEEE), the National Radiation Protection Authority (NRPA).

Keywords**—**Electromagnetic Environment, Electric Field Strength, Mathematical Models.

I. INTRODUCTION

THE increasing number of radio frequency emitters (radio, television, wireless communication, etc.) and the growing need of covering wider territories for wireless radio communication have caused an increase in the spatial density of radiated electromagnetic fields. This field level sometimes exceeds the guidelines for electromagnetic safety (EMS) [1], [2] and the proper operation of radio communication equipment thus resulting not only to economic and other risk but also environmental health issues. Therefore, public concern regarding human safety (health risk) associated with these increased Radio Frequency Radiation levels have emerged [3]–[5]. This has led to an important field of study in electromagnetic pollution and electromagnetic safety.

The electromagnetic environment (EME) is the sum of electromagnetic fields from various radio communication devices and natural electromagnetic processes at a given geographical location in space and time [6]. The ability for a radio communication equipment to operate with the required QoS at a given location in space and time is completely determined by the electromagnetic environment (EME) and the technical specifications of the equipment. Therefore, EME can affect the functionality of both the communication equipment and/or human health thus explains the need for its characterization. The complexity of EME is due to the increased number of sources of electromagnetic radiation. Technological development in radio communication engineering like wireless networks has led to a significant concentration of radio communication devices which are sources of electromagnetic radiation, especially in large urban cities.

The Electric field strength from a given radiation source at a location p_i is affected by multiple factors [6] including: distance from the source, frequency of the Electromagnetic field (EMF), the transmission power of EMF from source, type of modulation used (pulsed or unpulsed), environment (terrain, buildings and or materials in between the source and the location) etc. The EMF strength at any location is usually erratic due to the random nature of the propagation environment; this means that measurements made at different times and under different conditions at the same location will vary widely. Therefore momentary or single-point-in-time measurements can be quite misleading. A more informed result is one that would collect measurements over time, under different traffic conditions, season of the year, transmission activity. Therefore, adequate information on the EME for a given location is obtained by measurement on site because the measurements obtained from one location cannot be directly applied to another location characterised by a different environment. The two key factors in making accurate, repeatable EMF measurements are:

- Good measurement procedures
- Proper use of appropriate instruments

The measurements of Electric Field Strength can be carried out by means of the mobile measurement setup [7] shown in Fig. 1.

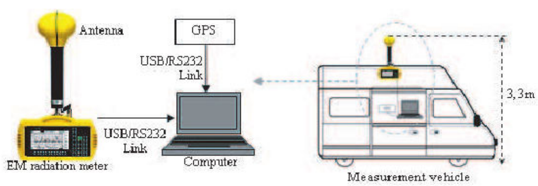

Fig. 1 Mobile Measurements Setup

The EM radiation meter can be the ***Radio frequency (RF) field probes*** which are often preferred for electromagnetic fields measurement because of being fast, simple and

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convenient. In general, RF probes have wide operation frequency but are not selective. It is essential to measure the combined field levels for all different signal sources in the analysis area and to quickly collect data as much as possible. ***A wide band spectrum analyser*** capable of being operated in a sweeping time mode over the frequency range of interest is used for frequency selective measurements.

Statistical analysis of the measurement data taken over time at every location is carried out and using statistical test like the t-test or the Dickey-Fuller (D-F) [7] to determine if the time series (a group of measurement results recorded over time) is suitable for estimation of field strength value. The estimated value is then compared to the reference levels for general public exposure guidelines given by recognised bodies like ICNIRP, ANSI / IEEE, NRPA. An example of such exposure limits guidelines for members of the public as recommended by ICNIRP and adopted by some countries [2] are presented in Table I.

TABLE I
RADIO FREQUENCY AND MICROWAVES RADIATION EXPOSURE LIMITS

Country	Radio Frequency and Microwaves Frequency range	Electric Field Strength E (V/m)	Power Density S (mW/cm^2)
USA/ANSI	100MHz – 1GHz	61.4(f/100)	f/100
IEEE	1GHz – 300GHz	194.16	*10*
MALAYSIA	300 MHz – 1.5GHz	$1.616f^{1/2}$	f/1500
MCMC	1.5GHz – 300GHz	62	1

The experimental approach in the characterization of such complex EME is associated with high cost and it is also time consuming. It could also be excluded because of one reason or another. The alternative method to measurement for carrying out such analysis is modelling and simulation based on appropriate mathematical models of radio transmitters, radio receiver receptivity, antenna feeder units, radio wave propagation [8], and different noise and interference mechanisms.

If the electromagnetic environment (EME) is characterised **over time** by any of the above methods it can enable the electric field strength at every point in the analysis area to be determined. This result of electric field strength is then used to estimate the signal to noise ratio (for the proper operation of the communication equipment) and the exposure levels of Radio Frequency Radiation (for human safety) at every point in the analysis area. The results are then interpreted based on comparison of the determined:

- Signal to noise ration with the guide lines established by ITU and national communication regulatory agencies
- Radio Frequency Radiation exposure level with the safe guidelines for general public exposure given by recognised body such as WHO, the International Commission on Non-Ionising Radiation Protection (ICNIRP), Institute of Electrical and Electronic Engineers (IEEE), the National Radiation Protection Authority (NRPA).

The remainder of this paper is organised as follows: Section II considers the categorization of the different sources of electromagnetic radiation industrial noise, Natural noise and different transmitters. In Section III, we describe the analysis area for the purpose of analysing the EME by modelling and simulation. The description of the EME as a set of several surface sections is given in Section IV.

II. COMPONENTS OF EM RADIATIONS

The EME is made up of electromagnetic radiations from sources classified as Natural and Industrial noise and also radiations from different type of radio communication transmitters as shown in Fig. 2.

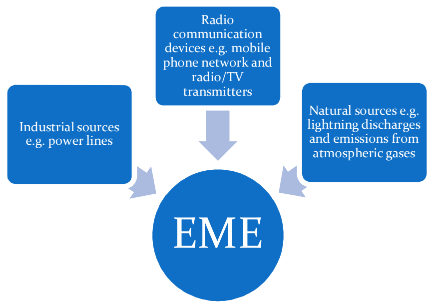

Fig. 2 Components of EME

The sources of radiation responsible for the industrial noise and also radiations from different type of radio communication transmitters are located on the analysis area of interest and are described by their geographical coordinates. The next section gives the description of the analysis area for the purpose of analysing the EME by modelling and simulation.

III. DEFINITION OF THE ANALYSIS AREA

The analysis area (AA) will be defined by making use of the geographical coordinates of all the relevant EM sources as a rectangular area bounded by minimum and maximum longitude (Lon_{max}, Lon_{min}) on the horizontal direction and also by minimum and maximum latitude (Lat_{max}, Lat_{min}) on the vertical direction. This area therefore contains all the base stations of the network. The rectangle thus formed is then divided as a uniform grid with steps ΔLon and ΔLat in the longitude and latitude axes respectively as shown in Fig. 3.

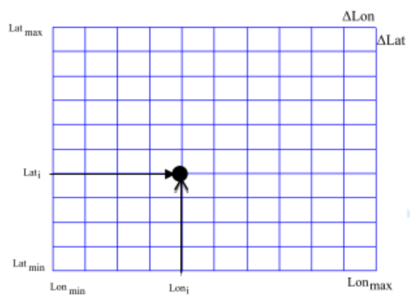

Fig. 3 Defining the Analysis Area

$$\Delta Lon = \frac{Lon_{max} - Lon_{min}}{n_{Lon}}, \qquad (1)$$

$$\Delta Lat = \frac{Lat_{\max} - Lat_{\min}}{n_{Lat}}, \quad (2)$$

where n_{Lon}, n_{Lat} are the number of cells in the respective longitudinal and latitudinal directions.

The various sources of electromagnetic radiations are all deployed in the analysis area according to the coordinates and the EME is estimated for each node in the rectangular grid. The map of the EME can then be plotted or superimposed on the geographical map of the analysis area.

IV. Description of EME

The far field power of the electromagnetic field received Pr from a distant transmitter is calculated using the formula:

$$\Pr = f\left(P_{tx}, L_{tx}, G_{tx}, L_p, G_{rx}, L_{rx}\right), \quad (3)$$

where, P_{tx} is the transmitter power which may be random due to power control issues, L_{tx} is the transmitter losses, G_{tx} is the transmit antenna gain, L_p is the path loss characterizing the channel and is a random function of frequency, distance, environment and time - $L_p = f(\textit{frequency}, \textit{distance}, \textit{environment}, \textit{time})$, G_{rx} is the receive antenna gain and L_{rx} is the receiver losses.

The EME in the HF and VHF range in a given location in space p_i and at time t consist of electromagnetic fields of the wanted signal, interference and noise. Assuming statistical independence of the component fields and the linearity of the antenna-feeder device within the frequency band Δf at the input of the receiver, then the total power of the fields $P(p_i, f, t)$ with frequency f at location p_i and time t can be expressed by (4):

$$P(p_i,f,t) = \sum_m P_{S,m}(p_i,f,t) + \sum_j P_{I,j}(p_i,f,t) + \sum_k P_{N,k}(p_i,f,t), \quad (4)$$

where, $P_{S,m}(p_i,f,t)$ is the m-th wanted signal power at frequency f in location p_i and at time t; $P_{I,j}(p_i,f,t)$ is the j-th interference power at frequency f in location p_i and at time t; $P_{N,k}(p_i,f,t)$ is the k-th noise source power at frequency f in location p_i and at time t.

The relationship between power and electromagnetic field strength E in the far field in the location of the receiver is given by (5):

$$P = \frac{E}{R_0} A_{eff} = \frac{E^2 \lambda^2 G}{4\pi R_0 \eta}, \quad (5)$$

where, E is electromagnetic field intensity at the of receiver antenna location; $R_0 = 120\pi\Omega$ is free space impedance; G is Receiver antenna gain; η is Receiver feeder losses.

Considering the relationship in (5) and assuming that $\Delta f << f$ then (4) can be written in the form:

$$E(p_i,f,t) = \sqrt{\sum_m G_{S,m} E^2_{S,m}(p_i,f,t) + \sum_j G_{I,j} E^2_{I,j}(p_i,f,t) + \sum_k G_{N,k} E^2_{N,k}(p_i,f,t)} \quad (6)$$

Expression (6) enables the characterization of the energy parameters of electromagnetic environment as a function of space coordinates, frequency and time. The function $E(p_i,f,t)$ for a location p_i in the area of interest (henceforth referred to as **analysis area**) can be obtained by experiment i.e. by carrying out field measurements using appropriate tools and methods or by modeling and simulation i.e. by using computer experiments with appropriate models [6]. The value of $E(p_i,f,t)$ determined by measurement or estimated by simulation represents the EME at the location p_i.

Consider one frequency channel corresponding to the frequency f_o of a radio system at a fixed location p_i at time t_o. In this case (6) can be written as shown in (7):

$$E(p_i,f_o,t_o) = \sqrt{\sum_m G_{S,m} E^2_{S,m}(p_i,f_o,t_o) + \sum_j G_{I,j} E^2_{I,j}(p_i,f_o,t_o) + \sum_k G_{N,k} E^2_{N,k}(p_i,f_o,t_o)} \quad (7)$$

If the wanted signal to noise plus interference ratio at the location p_i and time t_o and frequency f_o represented by $h(p_i,f_o,t_o)$ is given by (8):

$$h^2(p_i,f_o,t_o) = \frac{G_S E_S^2(p_i,f_o,t_o)}{\sum_j G_{I,j} E^2_{I,j}(p_i,f_o,t_o) + \sum_k G_{N,k} E^2_{N,k}(p_i,f_o,t_o)} \quad (8)$$

Then the electric field intensity can be expressed in the form of (9):

$$E(p_i,f_o,t_o) = G_S E_S(p_i,f_o,t_o)\sqrt{1 + \frac{1}{h^2(p_i,f_o,t_o)}} \quad (9)$$

The value of the electromagnetic field intensity obtained using (9) will determine whether a radio communication receiver operating at frequency f_o will function with a required QoS at the given location in space p_i, and time t_o. In general, the function $E(p_i,f,t)$ defines a five-dimensional surface section $E(x_i,y_i,z_i,f,t)$, representing the different characteristics of the electromagnetic environment. Therefore, the set of values $E(x_i,y_i,z_o,f_o,t_o) \rightarrow \{E_i\}$ represent an instant map (snapshot) of the distribution of EM field for a given frequency channel, height above the terrain z_o and at the time instant t_o. An example of a set of such maps $E(x_i,y_i,z_o,f_o,t_o)$ where $n = 1,2,3,4,......$ obtained by processing measurement in the operating frequency band of a cellular communication system is shown in Fig. 4.

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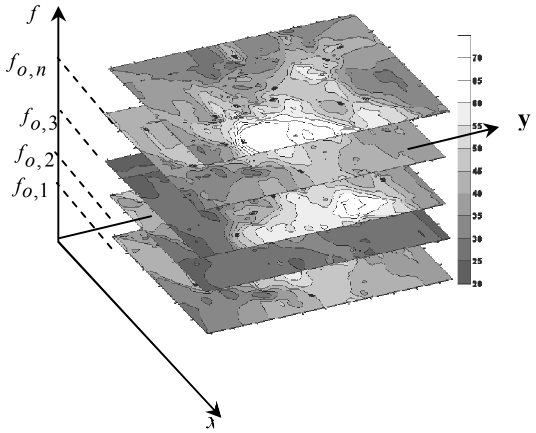

Fig. 4 Maps (Snapshots) of the distribution of the intensity of EMF

$E(x_i, y_i, z_o, f, t_o) \rightarrow \{E_i(f)\}$ is the instantaneous spectrum at a given location in space. An example of the spectrum of the frequency channels of a cellular communication system in the instantaneous 7 MHz band is shown in Fig. 5. Instant spectrum contains information about all the components in (6), which may be obtained by proper processing of the spectrum.

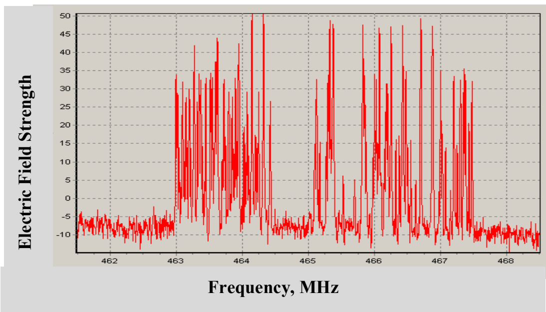

Fig. 5 Instantaneous spectrum

The instantaneous spectrum obtained by using a spectrum analyser capable of being operated in a sweeping time mode over a broad frequency range containing different communication services has the form shown in Fig. 6.

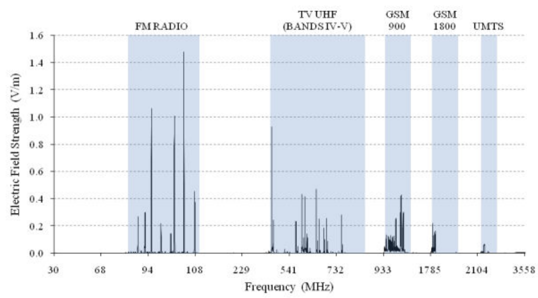

Fig. 6 Instantaneous spectrum

$E(x_i, y_i, z_o, f_o, t) \rightarrow \{E_i(t)\}$ illustrates the time dependence or fluctuations of the EM field distribution map for the given frequency channel at a fixed height z_o and frequency f_o.

$E(x_i, y_i, z_o, f, t) \rightarrow \{E_i(f, t)\}$ represents the evolution of the electromagnetic field spectrum in time at a given point in space. An example of a spectrum time evolution (spectrogram) is shown in Fig. 7.

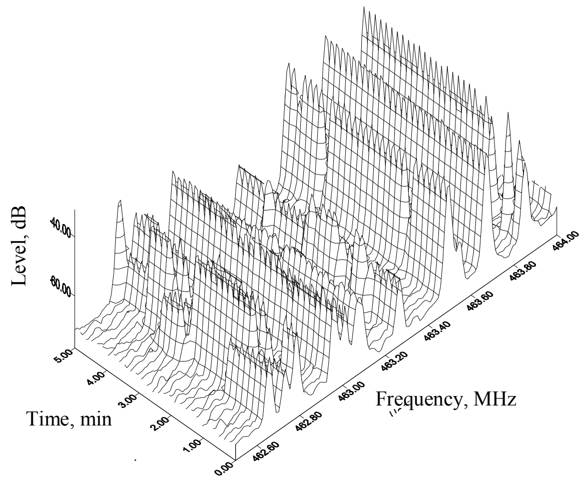

Fig. 7 Time evolution of a spectrum (spectrogram)

Thus, the state of EME can be characterized by a set of several surface sections $E(p_i, f, t)$: **maps** of the distribution of the EM field intensity, **spectrum** and the **characteristics of the time** traffic loading of radiofrequency spectrum.

V. Conclusion

This paper has considered the characterisation of a complex electromagnetic environment due to multiple sources of electromagnetic radiation as a five-dimensional surface which can be described by several surface sections including: instant EM field intensity distribution maps at a given frequency and altitude, instantaneous spectrum at a given location in space and the time evolution of the electromagnetic field spectrum at a given point in space. This characterization if done over time can enable the exposure levels of Radio Frequency Radiation at every point in the analysis area to be determined

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