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.

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
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) 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.

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.

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 ∆Lon and ∆Lat in the longitude and latitude axes respectively as shown in Fig. 3.

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.

### TABLE I

<table>
<thead>
<tr>
<th>Country</th>
<th>Radio Frequency and Microwaves Frequency range</th>
<th>Electric Field Strength E (V/m)</th>
<th>Power Density S (mW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA/ANSI</td>
<td>100MHz – 1GHz</td>
<td>61.4(f/100)</td>
<td>£100</td>
</tr>
<tr>
<td>IEEE</td>
<td>1GHz – 300GHz</td>
<td>194.16</td>
<td>10</td>
</tr>
<tr>
<td>MALAYSIA</td>
<td>300 MHz – 1.5GHz</td>
<td>1.616f</td>
<td>£1500</td>
</tr>
<tr>
<td>MCMC</td>
<td>1.5GHz – 300GHz</td>
<td>62</td>
<td>1</td>
</tr>
</tbody>
</table>

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.
\[ \Delta R = \frac{L_{\text{max}} - L_{\text{min}}}{n_{\text{lat}}}, \tag{2} \]

where \( n_{\text{Long}}, n_{\text{Lat}} \) 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 \( P_r \) from a distant transmitter is calculated using the formula:

\[ P_r = f(P_{tx}, L_{tx}, G_{tx}, L_p, G_{rx}, L_{rx}), \tag{3} \]

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, \( G_{rx} \) 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 receiver, then the total power of the fields \( P(\phi,f,t) \) with frequency \( f \) at location \( p_i \) and time \( t \) can be expressed by (4):

\[ \sum_{m} P_{m}(\phi,f,t) = \sum_{j} P_{j}(\phi,f,t) + \sum_{k} P_{k}(\phi,f,t), \tag{4} \]

where, \( P_{m}(\phi,f,t) \) is the m-th wanted signal power at frequency \( f \) in location \( p_i \) and at time \( t \); \( P_{j}(\phi,f,t) \) is the j-th interference power at frequency \( f \) in location \( p_i \) and at time \( t \); \( P_{k}(\phi,f,t) \) 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):

\[ P_r = \frac{E^2}{2\eta} \cdot \frac{20}{\log_{10}}, \tag{5} \]

where, \( E \) is electromagnetic field intensity at the of receiver antenna location; \( R_0=120\log_{10} \) is free space impedance; \( G \) is Receiver antenna gain; \( \eta \) is Receiver feeder losses.

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

\[ E(\phi,f,t) = \frac{\sum_{j} P_{j}(\phi,f,t) + \sum_{k} P_{k}(\phi,f,t)}{\sum_{m} P_{m}(\phi,f,t)} \tag{6} \]

Expression (6) enables the characterization of the energy parameters of electromagnetic environment as a function of space coordinates, frequency and time. The function \( E(\phi,f,t) \) 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 \( E(\phi,f,t) \) determined by measurement or estimated by simulation represents the EME at the location \( p_i \).

Consider one frequency channel corresponding to the frequency \( f_0 \) of a radio system at a fixed location \( p_i \) at time \( t_0 \). In this case (6) can be written as shown in (7):

\[ h^2(\phi,f_0,t_0) = \frac{G_{rx}^2}{\sum_{j} P_{j}(\phi,f_0,t_0) + \sum_{k} P_{k}(\phi,f_0,t_0)} \tag{7} \]

If the wanted signal to noise plus interference ratio at the location \( P_j \) and time \( t_0 \) and frequency \( f_0 \) represented by \( h^2(\phi,f_0,t_0) \) is given by (8):

\[ h^2(\phi,f_0,t_0) = \frac{G_{rx}^2}{\sum_{j} P_{j}(\phi,f_0,t_0) + \sum_{k} P_{k}(\phi,f_0,t_0)} \tag{8} \]

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

\[ E(\phi,f_0,t_0) = \frac{G_{rx}}{h^2(\phi,f_0,t_0)} \tag{9} \]

The value of the electromagnetic field intensity obtained using (9) will determine whether a radio communication receiver operating at frequency \( f_0 \) will function with a required QoS at the given location in space \( p_i \) and time \( t_0 \). In general, the function \( E(\phi,f,t) \) defines a five-dimensional surface section \( E(x_1,y_1,z_1,f,t) \), representing the different characteristics of the electromagnetic environment. Therefore, the set of values \( E(x_1,y_1,z_1,f,t) \) represent an instant map (snapshot) of the distribution of EM field for a given frequency channel, height above the terrain \( z_0 \) and at the time instant \( t_0 \). An example of a set of such maps \( E(x_1,y_1,z_1,f,t) \) where \( n = 1,2,3,4, \ldots \) obtained by processing measurement in the operating frequency band of a cellular communication system is shown in Fig. 4.
Fig. 4 Maps (Snapshots) of the distribution of the intensity of EMF

\[ E(x_i, y_i, z_0, f, t) \rightarrow [E_i(f)] \] 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.

\[ E(x_i, y_i, z_0, f, t) \rightarrow [E_i(f)] \] illustrates the time dependence or fluctuations of the EM field distribution map for the given frequency channel at a fixed height \( z_0 \) and frequency \( f_0 \).

Fig. 6 Instantaneous spectrum

\[ E(x_i, y_i, z_0, f, t) \rightarrow [E_i(f)] \] 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 \( E(x_i, f, t) \): 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.

REFERENCES


[2] Review of the scientific evidence on dosimetry, biological effects, epidemiological observations, and health consequences concerning exposure to high frequency electromagnetic fields (100 kHz to 300 GHz), ICNIRP 16:2009.


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