2023 IEEE Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMC+SIPI) | 979-8-3503-0976-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/EMCSIPI50001.2023.10241622

An Alternative Perspective on Time Domain Electromagnetic Field Measurement in Hospital Environment

Rıdvan Aba[1]
[1]*University of Twente*
Enschede, The Netherlands
ridvan.aba@utwente.nl

Robert Vogt-Ardatjew[1]
[1]*University of Twente*
Enschede, The Netherlands

Frank Leferink[1,2]
[1]*University of Twente*
Enschede, The Netherlands
[2]*Thales, Nederland B.V.*
Hengelo, The Netherlands

***Abstract*—Electromagnetic environment characterization of complex environment such as a hospital is a challenging issue due to the dynamic characteristics like field fluctuations over time as well as space, and multiple interference sources within. This paper proposes an alternative perspective on electromagnetic environment characterization depending on E-field probe measurements. A hospital is known to be a semi-reverberant, and often undermoded environment. For this reason, in this paper, it is considered to be similar in behavior to a vibrating intrinsic reverberation chamber (VIRC), operating in undermoded region. The measurements were performed using 3-axis E-field probes at nine different locations inside a VIRC. It was aimed to characterize the environment using 3-axis E-field probe measurement results by considering the concept of ergodicity. Finally, the probability distributions were observed.**

Keywords—EMI-risk based approach, E-field probe, vibrating intrinsic reverberation chamber, probability distribution, environment characterization

I. Introduction

The implementation of new technologies such as wireless communication networks, electrosurgery, magnetic resonance imaging (MRI) and computer tomography (CT) has changed the electromagnetic environment in the hospital in the last decade. Due to its ease of installation and use, a large deployment is observed especially in Bluetooth and WLAN technologies. Almost every person has at least one mobile phone nowadays. Not only mobile phones but also laptops, smart watches, tablets, mouses, keyboards, and even doors and windows are using wireless communication networks. The devices used in wireless communication networks, together with the unintentional radiated emissions of the huge amount of installed electronics, create electromagnetic fields (EMF). Every equipment used for various purposes, ranging from surgical knives to power grids in the hospital environment contributes to or is affected by the aforementioned EMF. One of the most remarkable points is that the hospital is an environment where the latest technology and old technology are intertwined. Therefore, the possibility of electromagnetic interference (EMI) increases because the EMI design criteria of old-fashioned devices are not the same as those of cutting- edge-technology devices. Figure 1 clearly shows the increase in wireless communication, transmission issues or radio signal problem numbers in the last ten years

This project has received funding from the European Union's EU Framework Programme for Research and Innovation Horizon 2020 under Grant Agreement No 955.816.

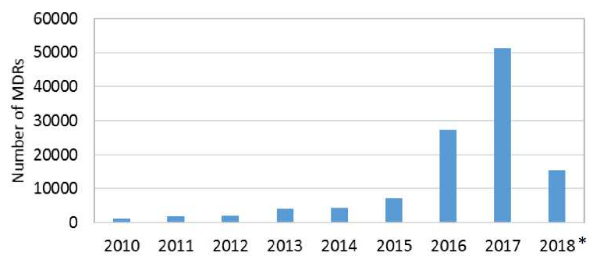

Fig. 1. Wireless communication or transmission issue or radio signal problem [1]

There exist various international standards that guide electromagnetic compatibility (EMC) issues and specify the permissible emission and susceptibility levels in the hospital environment like [2],[3]. However even though all the medical equipment are tested considering the EMC standards, following the rule-based approach, the EMI issues in hospital are inevitable due to the limited control of such a complex environment. Hundreds of thousands of EMI issues in hospital environment were reported in the last decade [4]. This could be explained as a deficiency in the rule-based approach, which is based on (testing against) standards. The major problem with the rule-based approach is that the devices are tested in special test environment, under certain conditions, certain test distances, though the deployed equipment could be exposed to very different configurations and environmental factors throughout their life cycle. Hence, an alternative approach named the risk-based approach was proposed and the necessity of this approach to be applied to dedicate the ignored situations in the rule-based approach was explained with examples [5],[6].

The risk-based approach has successfully been applied to the hospital environment in e.g. [7], among others. In this study, stationary radiated emission measurements were performed for the 30 MHz – 1 GHz band using a biconical antenna and spectrum analyser while the conducted emission measurements were carried out using a current probe and a spectrum analyser. It was shown that although all the medical equipment has been tested for EMC, an EMI risk still exists. In [8], the stationary short- and long-term measurements were performed in different locations of a hospital to observe the time as well as the location dependency of the EMF in a hospital. Even though the aforementioned studies demonstrate remarkable results, the stationary measurement method was utilized for these studies. An effective measurement method, based on the random-walk technique, was proposed and applied to electrically large reflective spaces [9]. This technique was also applied to the hospital environment and concluded with evaluating the hospital environment in terms of risk-based EMC [10]. Another study that compares the fixed position and random-walk measurement techniques in terms of EMI risk-based EMC evaluation for the automotive environment was introduced in [11]. Each of the above-mentioned measurement techniques has some advantages as well as disadvantages because a hospital is still a complicated and hard-to-fully-describe environment due to its unexpected EM behaviour in both time and space. The long-term stationary measurement technique is a good solution in terms of covering the time dependency but the location dependency is missed. As for the random-walk technique, it may be thought to be a near-perfect technique at first glance, but it is an indisputable fact that this technique also has weak points. Since the measurements are performed while randomly walking around, the field fluctuations of a single point in the time domain, i.e. what a static victim would experience, are missed. Also, a commonly-used spectrum analyser is locked to a certain narrow frequency band which means a remarkable part of the frequency range is overlooked. Moreover, the spectrum analyser has a disadvantage due to its sweep time [12]. One cannot make more than one sweep simultaneously which means there is always the probability of missing the impulsive field components (unless novel real-time spectrum analysers are used, although their instantaneous bandwidth are still limited).

In this study, we propose looking from a different perspective at the measurement procedure and the characterization of the E-field levels in a hospital. The measurements were performed using fast, broadband electric fields to overcome the disadvantages of the spectrum analyser on sweep time and narrow frequency bands. With this method, the frequency information of the individual components is missed, but the question to ask is whether the frequency information is more important than the others. We focus on measuring the electric field levels created by a single-tone signal inside a vibrating intrinsic reverberation chamber (VIRC) to understand the behaviour of this controlled environment. This study has three main objectives. First, to understand the differences and similarities between an ideal overmoded cavity and a hospital room, commonly undermoded [13], by performing the measurements in both undermoded and overmoded frequency regions of the VIRC. Second, to create some confidence intervals for maximum E-field levels. Finally, utilizing the ergodicity concept, to make predictions for the locations where the measurements were not performed using a limited number of measurements. Of course, we do not make a big leap in terms of measurement tools but the idea of measurement is expected to offer some important insights into the characterization of the hospital environment. The intention of this paper is to deploy a number of E-field probes to a hospital and characterize environment in terms of E-field levels. The paper is organized as follows: in Section II, the measurement premises are described in detail. In Section III, the measurement setup is explained. In Section IV, the representative VIRC measurement results are given. In Section V, depending on the analysis of the measurements, we make some considerations for the risk-based EMC approach, and Section V concludes the paper.

II. Measurement Premises

A. Ergodicity Concept

Ergodicity is a concept that is fuzzy by definition and difficult to see in terms of application. Since the purpose of this study is not to explain the ergodic theory in all its aspects, we will only briefly mention it for the sake of clarifying the scope of the work presented in this paper. The ergodic theory focuses on the statistical analysis of dynamical systems considering the measurement spaces of that system [14]. The theory mentions that the time average of measurements performed along a trajectory under certain conditions gives the average measurement over the entire system [14]. Ergodicity, which seems easy to prove by looking at this simple explanation, is a concept that requires a complex proof procedure. If we take a closer look at the words we use in definition, we realize that they are ambiguous words. First of all, the measurement procedure is one of the key points of the ergodicity concept because, for a perfect measurement, we need to make a continuous and infinite number of measurements, which is impossible. Secondly, time or time average is another issue to consider because the expected value for a dynamic system brings with it the question of how long the measurement is made. The answer can be a minute, an hour, a day or a year, and this is a remarkably important issue that needs to be approached carefully. Third, the measurement trajectory is another noteworthy point. Whether the measurement will be made along a trajectory or by selecting certain locations is, of course, a question that needs to be answered in terms of practice. Since the aforementioned environment is a hospital, it is more difficult than it is thought to make measurements for a long time with measurement equipment in an environment where there are many patients and they are usually on the move. Finally, considering the ergodicity concept, the most important point of this measurement method is how many different points the measurements are made in.

As mentioned before, especially in the hospital environment, which is known to be a complex, dynamic and semi-reverberant environment, it is necessary to make an infinite number of measurements at an infinite number of points to estimate the maximum electric field level that can be observed. But since this is not possible in real life, we have to be content with measuring at a certain number of points. As a result of this, of course, we are moving away from a precise measurement because, as mentioned before, it is known that the hospital environment is undermoded. Because mode density and area distribution are not uniform in a undermoded environment, it is an incontrovertible fact that some of the measurement points are likely to stay in the hotspot and some in the cold spot. To overcome this disadvantage, measurements should be made at as many points and polarizations as possible. However, another point to be noted is that this number should not be too large for the applicability of the method.

B. Time-domain approach

The most common technique used for the characterization of a complex environment such as a hospital is the frequency-domain approach [8],[15]. As mentioned before, fixed-position stationary short- and long-term measurements are typically performed using a spectrum analyser. Similarly, the random-walk technique was also using the same equipment [9]. However, this method suffers from some weaknesses. First of all, the spectrum analyser can sweep the frequency band at a certain time. It is not possible to suddenly sweep the whole frequency band using a spectrum analyser yet. Another weakness of the spectrum analyser is that the user has to focus on a certain frequency band. If there is an intermittent emission outside of this band, the spectrum analyser will not be able to measure it. Some spectrum analysers allow the frequency range to be widened considerably, but in this case, the sweep time must be waived and vice versa. Finally, the spectrum analyser has to be used with a separate matched antenna, which becomes bulky at lower frequencies.

The core idea of this study is that frequency information is not necessary when performing statistical analysis of the electric field level in the hospital. Because in practice, if it can be observed that the electric field level is below a certain value in a very wide frequency range, it can be said to be below this level in a more specific frequency range. Also, since the hospital is a dynamic environment, the time-dependent variability of the electric field level is another point to be noted. For the reasons mentioned above, instead of frequency-domain measurement, time-domain measurement was decided to be performed. In this regard, the use of broadband, fast electric field probes is quite logical. In addition, these probes allow us to get very close to continuous time measurements with very high sampling rates. Moreover, the data streaming feature allows instant data to be saved on the computer.

C. Electromagnetic disturbance aspect

As previously mentioned, all medical equipment must comply with the various EMC standards. One of these tests is the radiated immunity test. During radiated immunity test a certain level of the electric field is created using various antennas and applied to the equipment under test (EUT). Throughout the test, EUT is monitored and it is observed whether there is a disturbance or not. Finally, the frequencies that the EUT shows vulnerability are reported.

If we think about the radiated immunity of an EUT and modelling this state, it is common to model a device that is sensitive to a certain electric field in a certain frequency range using an antenna operating at that frequency. In this case, a very tricky question may come to mind, such as what if the EUT is sensitive to this electric field for all frequencies? In this case, it makes sense to use a broadband electric field probe to successfully model the EUT.

III. Measurement Setup

The measurements were performed in a 1 m x 1.2 m x 1.5 m VIRC with nine fast, small, broadband E-field probes and a transmitting antenna. Eight probes were located at the corners and one at the centre of the working volume. The measurement setup is given in Figure 2. A single-tone signal was applied using a signal generator with fixed output power for all frequencies.. A broadband log-periodic dipole antenna was used as a transmitter. Due to the dimensions, the lowest usable frequency of the VIRC is around 400 MHz, but we performed the tests from 200 MHz to 2 GHz. Thus, we have established a test setup that can better model the hospital environment since it also covers the undermoded frequency region of VIRC where it does not work with high performance. In the undermoded region since the VIRC does not work properly, the field uniformity is low and mode density is low compared to the overmoded region. In this way, some probes will be in the cold spot while some will be in hot spots, including mechanical stirring. The behaviour of the field generated under these conditions can therefore mimic the environment found in a hospital.

Fig. 2. Measurement setup with 9 electric field probes

Fig. 3. Crossection of electric field probes used for measurements [16]

The E-field probes used in this study are optically-powered and has 0.5 MS/s in streaming mode. The frequency band it covers is from 10 kHz up to 6 GHz. As shown in Figure 3, the probe contains three-perpendicular monopole antennas to measure the electric fields in the x-, y- and z-axes. Since the monopole antennas are perpendicular, each can be considered a different antenna. Therefore, performing the measurements with nine probes means having 27 independent sets of measurement for each instance.

Measurements were performed for 5 seconds for each frequency. This means 2.5 M samples per measurement set. Considering 27 coordinates, it reaches 67.5 M samples for each frequency. We have done down-sampling to alleviate the burden of processing such a large amount of data. Instead of 0.5 MS/s, the data was down-sampled to 2 kS/s which is still high with respect to the coherence time of this chamber. Also, since the core idea of this study is not to end up with perfectly precise measurement results but to offer a new perspective on environment characterization, the results were analysed only for a few frequencies. Although this study can be extended to a more realistic situation, such as a real hospital setting, we limit this article to field analysis in a VIRC. The application in a real hospital environment is considered as a future study.

IV. Results & Discussion

In this section we represent the results obtained from the measurements. In Figure 4, the absolute field levels at each frequency for one probe is shown. 200 MHz and 400 MHz are in the undermoded region while 1000 MHz and 2000 MHz are in the overmoded region for this reason, the field level is higher and more stable in overmoded region compared to undermoded region.

In Figure 5 and Figure 6, the E-field levels of each axis are given for one probe at 200 MHz and 400 MHz respectively. In Figure 5 and Figure 6, each axis of the E-field probe was considered to be an independent antenna measuring electric field level. Comparing these figures, one can notice that the dominant field is in the x direction for 200 MHz, however at 400 MHz it is in the z direction. In Figure 7, it is obvious that the field levels are comparable for all axes at 1000 MHz, indicating an overmoded cavity. Since electric field probe is used and it measures the three axes simultaneously, it is not important in which axis the dominant electric field is. If we were using antenna instead, we would have to change the polarization of the antenna. Now, it makes sense to consider and analyze three axes of electric field probes as different antennas.

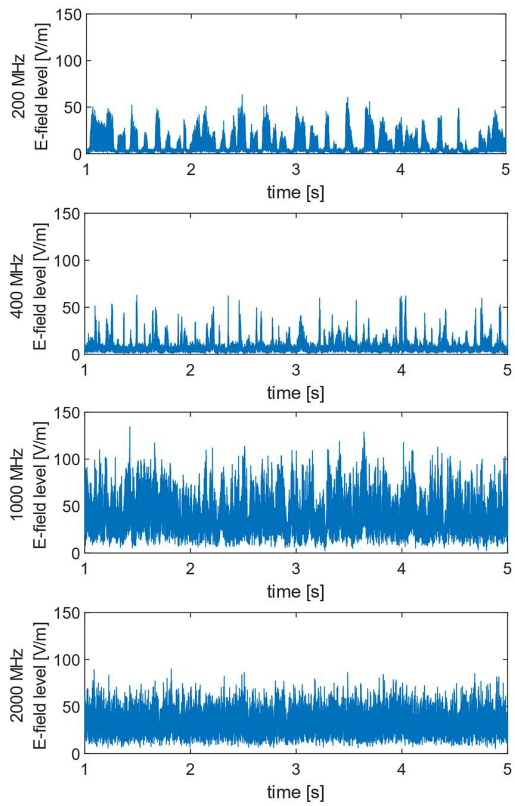

Fig. 4. E-field levels for one probe at each frequency

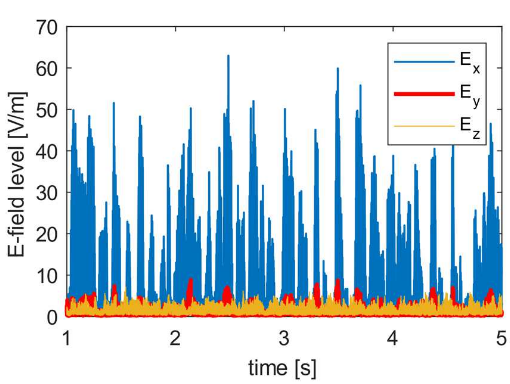

Fig. 5. E-field levels at 200 MHz for one probe at each axis

As previously mentioned, the hospital is commonly an undermoded, semi-reverberant environment. For this reason, 200 MHz and 400 MHz regions can be more useful for identifying and characterizing the hospital environment. Now, we focus on the distribution of E-field level at undermoded region. In Figure 8, the normalized histograms of E-field level at 200 MHz at each axes are given. From this figure, it is understood once again that 200 MHz is in the undermoded region because the normalized histograms do not fit the Rayleigh distribution. For 400 MHz, as seen from Figure 9, the histograms still do not fit the Rayleigh but an improvement

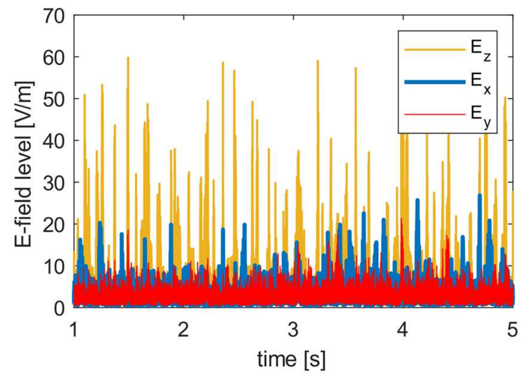

Fig. 6. E-field levels at 400 MHz for one-probe at each axis

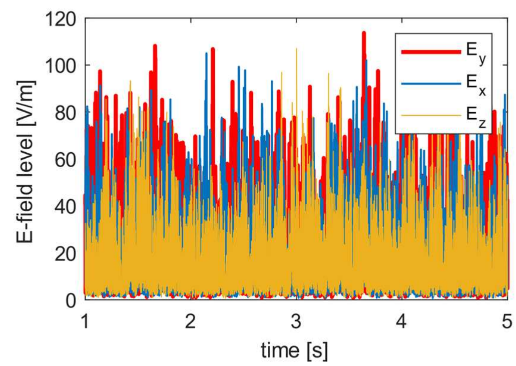

Fig. 7. E-field levels at 1000 MHz for one-probe at each axis

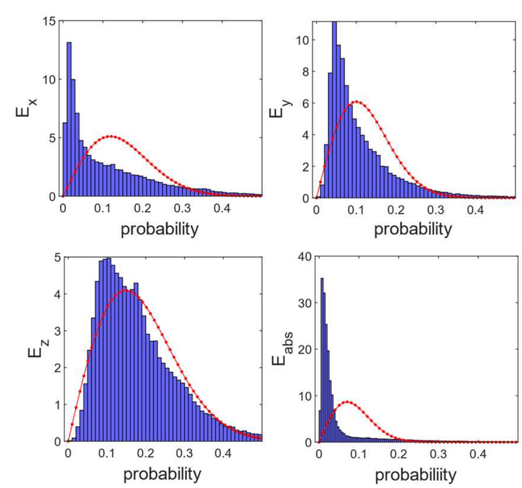

Fig. 8. Normalized histograms at 200 MHz for one probe at each axis

is obvious because 400 MHz is much more closed to the overmoded region.

Having explained one-probe situation, we now move on to discuss the multiple-probe situation to examine the effect of multiple-probe. Since all axes of E-field probe are independent, each probe has three independent measuring antenna. For n E-field probes means $3n$ independent measuring antenna. Regardless of fitting the Rayleigh curve we can make expectation from the distribution curves because the hospital is an undermoded region and the EM field in the hospital does not have to show a perfect Rayleigh distribution. Figure 9 and Figure 10 shows the probability distribution of four different situations at 200 MHz and 400 MHz respectively. However, as seen given in Figure 7, the distributions of each axes is different show different characteristics in one-probe situation, if each axes is taken as independent measurement point and analyzed independently, as seen in Figure 9 and Figure 10, the probability distribution takes a certain form. This observational study suggests that even if the measurements are performed in undermoded region and the distribution of electric field does not show a well-known distribution characteristics, if the number of independent measurements is increased and the overall measurements are analyzed together, then it is possible to end-up with a reliable probability distribution.

Finally, the probability distribution of electric field at 2000 MHz for one-probe situation is given in Figure 11. This figure shows that when the VIRC is in overmoded region, the field uniformity is satisfied and the field distribution almost fits the perfect Rayleigh distribution. Then, one could conclude that the environment is ergodic because no matter we perform a measurement along a trajectory or at a fixed point, we obtain the same results. Unfortunately the same approach could not be applied to undermoded region for one-probe configuration because the probability distributions are different for each axes and they can alter with frequency change. However, with increasing the number of measurement points, it is possible to converge a certain distribution and obtain an ergodicity-likely situation. This means if we perform even a small number of independent measurements, then it is possible to obtain a reliable probability distribution and analyze the environment successfully.

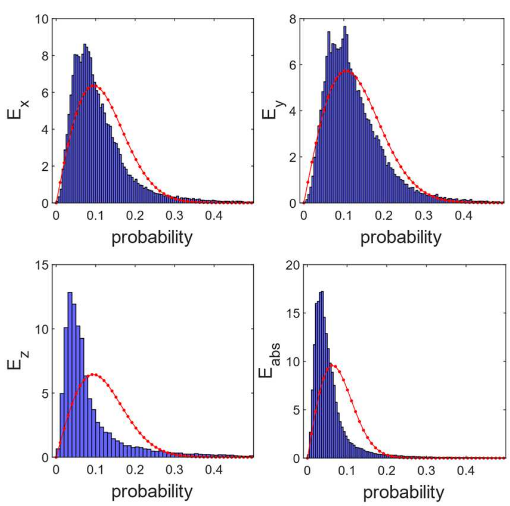

Fig. 9. Normalized histograms at 400 MHz for one-probe at each axis

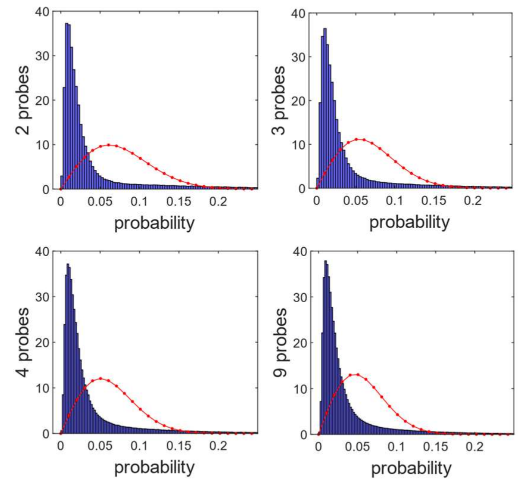

Fig. 10. Normalized histograms at 200 MHz for multiple-probe

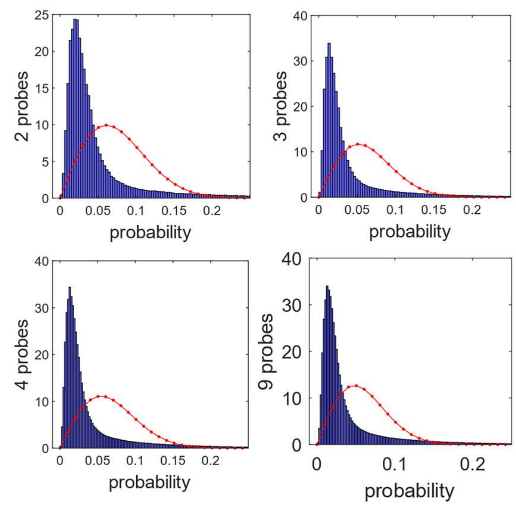

Fig. 11. Normalized histograms at 400 MHz for multiple-probe

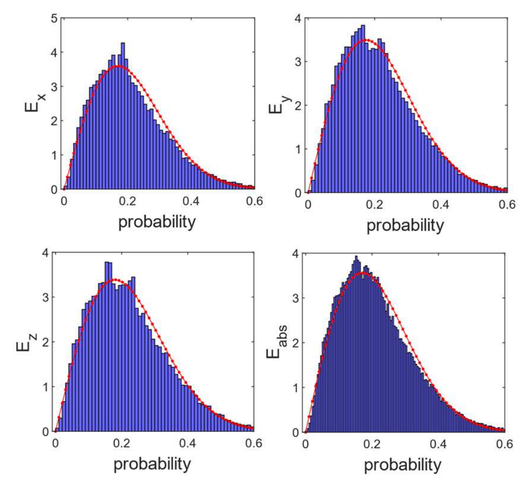

Fig. 12. Normalized histograms at 2000 MHz for one-probe at each axis

V. CONCLUSION

This paper suggests an alternative perspective on the EME characterization of complex environment such as hospitals. Instead of performing sweeps over frequency domain, the measurements were performed using fast, broadband, small E-field probes. Then, each axes of E-field probe were considered to be independent measurement units and the overall measurements were analyzed statistically. Although the hospital environment was modeled with an undermoded VIRC with a single-tone signal and the measurements were performed in this way, the results are not disappointing. By deploying a number of probes, the E-field in a hospital can be characterized. The findings have important implications for developing a method for EME characterization of complex environment such as hospital in terms of EMI-risk based approach.

Future work will be devoted to the study of the characterization of a real hospital environment by deploying a number of E-field probes. Further research in this field would be of great help in risk-based EMC approach.

REFERENCES

[1] J. L. Silberberg, "An FDA Perspective on Medical Device EMC and Wireless WED-PM-4," 2018 IEEE Symposium on Electromagnetic Compatibility, Signal Integrity and Power Integrity (EMC, SI & PI), Long Beach, CA, USA, 2018, pp. 1-84, doi: 10.1109/EMCSI.2018.8495328.

[2] International Electrotechnical Committee IEC/TC, “Medical electrical equipment-General requirements for safety Collateral standard: Electromagnetic compatibility - Requirements and tests (IEC 60601-1-2:2001),” Classification of Electromagnetic Environments, Tech. Rep., 2001

[3] Directive 2004/40/EC of the Europe Parliament and of the Council of 29 April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (18th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)

[4] J. L. Silberberg, "An FDA Perspective on Medical Device EMC and Wireless WED-PM-4," 2018 IEEE Symposium on Electromagnetic Compatibility, Signal Integrity and Power Integrity (EMC, SI & PI), 2018, pp. 1-84, doi: 10.1109/EMCSI.2018.8495328.

[5] F. Leferink, J. -K. van der Ven, H. Bergsma and B. van Leersum, "Risk based EMC for complex systems," 2017 XXXIInd General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS), 2017, pp. 1-4, doi: 10.23919/URSIGASS.2017.8105016.

[6] F. Leferink, "Risk-based vs Rule-based Electromagnetic Compatibility in Large Installations," 2018 IEEE 4th Global Electromagnetic Compatibility Conference (GEMCCON), 2018, pp. 1-4, doi: 10.1109/GEMCCON.2018.8628505.

[7] J. Evangelista, H. Loschi, E. T. Costa, R. Smolenski, N. Moonen and R. Vogt-Ardatjew, "Radiated and Conducted EMI by RF Fields at Hospital Environment," 2021 Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC), 2021, pp. 1-4, doi: 10.1109/APEMC49932.2021.9597035.

[8] O. Lauer, M. Riederer, N. Karoui, R. Vahldieck, E. Keller and J. Frohlich, "Characterization of the electromagnetic environment in a hospital," 2008 Asia-Pacific Symposium on Electromagnetic Compatibility and 19th International Zurich Symposium on Electromagnetic Compatibility, 2008, pp. 474-477, doi: 10.1109/APEMC.2008.4559915.

[9] G. B. Tait and M. B. Slocum, "Random-Walk Technique for Measuring the Electromagnetic Environment in Electrically Large Reflective Spaces," in IEEE Transactions on Instrumentation and Measurement, vol. 60, no. 3, pp. 1003-1009, March 2011, doi: 10.1109/TIM.2010.2064930.

[10] M. Das, R. Vogt-Ardatjew, B. van den Berg and F. Leferink, "Time-efficient EMI Risk Evaluation Method in a Hospital Environment," 2021 IEEE International Joint EMC/SI/PI and EMC Europe Symposium, 2021, pp. 857-861, doi: 10.1109/EMC/SI/PI/EMCEurope52599.2021.9559356.

[11] V. Gkatsi, R. Vogt-Ardatjew and F. Leferink, "On-Site Automotive Environment Measurements for a Risk-based EMC Approach," 2022 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI), 2022, pp. 443-448, doi: 10.1109/EMCSI39492.2022.9889626.

[12] V. Gkatsi, R. Vogt-Ardatjew and F. Leferink, "Evaluation of EM Vehicle Environment Measurement Methods for Risk-Based EMC Analysis," 2022 ESA Workshop on Aerospace EMC (Aerospace EMC), 2022, pp. 1-6, doi: 10.23919/AerospaceEMC54301.2022.9828833.

[13] Vogt-Ardatjew, R. A. (2017). Electromagnetic fields in reverberant environments.

[14] Brin, M., & Stuck, G. (2002). Introduction to dynamical systems. Cambridge university press.

[15] J. F. Coll, J. J. Choquehuanca, J. Chilo and P. Stenumgaard, "Statistical characterization of the electromagnetic environment in a hospital," 2010 Asia-Pacific International Symposium on Electromagnetic Compatibility, 2010, pp. 289-292, doi: 10.1109/APEMC.2010.5475847.

[16] https://lumiloop.de/products/lsprobe-laser-powered-e-field-probes/lsprobe-1-2/