On-Site Automotive Environment Measurements for a Risk-based EMC Approach

Vasiliki Gkatsi
University of Twente
Enschede, The Netherlands
vasso.gkatsi@utwente.nl

Robert Vogt-Ardatjew
University of Twente
Enschede, The Netherlands
r.a.vogtardatjew@utwente.nl

Frank Leferink
University of Twente, Enschede
Thales Nederland, Hengelo
The Netherlands
frank.leferink@utwente.nl

Abstract—**Due to the on-going changes in modern technologies, deeper investigation of the complex automotive electromagnetic environments is necessary. Since conventional standardized testing methods are lacking characteristics met in real automotive electromagnetic environments, a risk-based electromagnetic compatibility approach can conclude to detection of potential electromagnetic interference threats. A measurement of a real automotive electromagnetic environment is proposed and investigated using two different measurement methods addressing the temporal and spatial variations of the electromagnetic environment. This investigation reveals the complexity of real electromagnetic environments and the difficulty of them being sufficiently described to warrant electromagnetic compatibility due to continuously varying parameters over space, time, and frequency. The random-walk technique is applied and compared with a discrete static measuring technique of acquiring data. Examination of the collected data is made along with discussion on their possible application through statistical tools.**

Keywords—automotive, risk-based EMC, random-walk technique, statistical analysis

I. INTRODUCTION

Due to the rapidly growing new technologies such as 4G, 5G, Wi-Fi, the number of on-board electronic components and devices in modern vehicles increases. These technologies introduce new complexities in the automotive electromagnetic environment (EME) resulting in potential electromagnetic interference (EMI) issues that are difficult to be detected and therefore overcome. Thus, the interest in the characterization of these types of EMEs increases quickly aiming to minimize the risk of EMI and assure electromagnetic compatibility (EMC) [1]. So far, standardized EMC automotive techniques evaluate components [2] and complete vehicles [3] by following measuring techniques in fixed laboratory conditions. These EMC measurement procedures, however, isolate the system under test (SUT) since they do not always account for potential EMI threats found in real dynamic automotive environments [4]. Previous investigations have shown weaknesses when it comes to radiated emission and immunity standard test methods in the automotive as shown in [5] and [6], respectively. The measuring equipment [7] as well as the vehicle operational mode [5] seem to significantly change the results concluding in inconsistencies while conducting validation measurements. Therefore, there is need for new, more robust approaches to evaluate an SUT and its surrounding operational EME [8]. This way, the anticipated EMC behavior of the SUT can be better comprehended. The risk-based EMC approach which is introduced in [9] and accounts additionally for other risk-factors as e.g., functional safety [10] can be a useful tool for assessing an EME. An example of such an application is presented in [11], where a system analysis platform is introduced incorporating known and unknown sources in a common automotive EME. The risk-based EMC approach has also been applied in medical [12] and maritime EMEs [13].

Previous studies have pointed out the necessity to evaluate in-vehicle EMEs with measurements performed in laboratory [14] as well as real conditions [15]. The new embedded on-board technologies have created a more complex automotive EME and therefore, more investigations are made towards internal field distributions in vehicular [16] as well as aviation [17] systems. Devices such as field probes and spectrum analyzers (SAs) are applied to evaluate the EME of an SUT depending on the measured quantity of interest [18]. The importance of assessment of the EME of a vehicle caused the introduction of new patents which lean towards real conditions such as a 3D field scanner presented in [19] and the random-LOS measurement system verified in [20]. Furthermore, solutions are given with analytical [21] and numerical [22] tools compared further with measurements in real cases [23]. All the above-mentioned methods have the same goal of evaluating the automotive internal and external EME in the time or/and frequency domain. Even though these approaches give a good assessment of the EME of a vehicle, the continuously altered properties of the environment over space, time, and frequency result to extreme complexity, which is difficult to be described deterministically. Due to the geometry and materials of a vehicle, it can be described as a complex enclosed cavity acting as a reverberant environment, similar to a reverberation chamber (RC) [24]. Therefore, in vehicles, as with RCs, statistical analysis can be of great help [25] when it comes to estimation of the EME.

As also applied in standards [26], a conventional discrete measurement technique can be implemented to assess an EME. This technique collects data at specific, static positions in space, over time and frequency. Oppositely, the random-walk technique presented in [27], applies volume sampling to collect data of the EME over time, frequency as well as space. An application of the random-walk has also been implemented in an office environment representing a hospital in [28]. Each technique focuses on estimating the EME in different domains independently [18]. In this paper, a comparison between the two techniques is made with measurements performed in a combustion engine vehicle. The investigation concentrates on the effects of the continuously altered temporal and spatial properties of the automotive EME. Additionally, further use of the results via probabilistic tools such as e.g., Bayesian Networks [30] is proposed. Such an application can output the probability of occurrence of various incidents and can further help to minimize the risk of EMI occurring in a real dynamic EME.

In Section II of this paper the measurement setups of the two methods are shown. Section III presents the results along with a wide discussion on the temporal and spatial effects as

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well as usability of the output received values via the two approaches. Finally, Section IV concludes the paper.

II. MEASUREMENT SETUPS

To investigate and understand an automotive EME, two measurement methods were performed in a combustion engine vehicle. The vehicle with the engine off was parked in an open area parking lot surrounded by a changing number of vehicles and people. Although the car was parked, the surroundings were continuously changing, therefore a similar scenario is to be expected from a car in traffic, where the suggested measurement techniques can also be used. The measurement setup consisted of a portable real-time spectrum analyzer (RTSA) connected to a portable, omnidirectional, broadband, and linearly polarized antenna. The antenna in this case, acts as the victim in the 3-point risk-based EMC model presented in [11], but also giving information about the response to known and unknown sources in the EME. Even though in [11] the model allows to analyze each source independently, in this case all sources are considered as unknown, collectively creating the complex EME. It is important to notice that although the frequency components are measured individually within the sweep, the power in each of them is a sum of all the sources present in the EME, occupying that frequency. The frequency range of the measurements was 400 MHz to 4 GHz, incorporating bands of interest in the automotive such as GSM, etc., as well as covering the range where the vehicle chassis becomes reverberant, which is of crucial importance.

A. *Fixed position technique*

For this measuring technique, the discone antenna was collecting samples while placed in different discrete and stationary positions inside the vehicle. For this paper, two positions were selected to be investigated:

- Position FS: Driver’s seat (left side)
- Position BS: Back passenger’s seat (left side)

This discrete approach of measurements was selected to examine what it can offer regarding the EME analysis of the vehicle with respect to time-variance of individual frequency components. Additionally, the specific positions were selected to obtain data from different points inside the car to examine how the location of the receiving antenna can influence the output data. The RTSA was recording the data in the complete frequency range for 408 sweeps with sweep time equal to 145 ms. Three measurements were conducted at different times for each position.

B. *Random-walk technique*

A structure such as a vehicle can be referred to as a complex cavity, since it has an arbitrary shape, and therefore the electric field pattern at its interior can be chaotic [27]. Such complex structures, present a range of field values in different points at their interior due to the continuously changing conditions of the EME. An analogy in [24] has been made comparing a vehicle-like cavity to an RC. However, an RC is a fully reflective and controlled environment compared to a vehicle cabin which exhibits restricted reverberant properties due to apertures, losses, etc. The strong field values that should be of concern due to their high risk of causing EMI, appear unpredictably inside such a cavity. Therefore, like RCs, statistical tools can also be useful in vehicle applications. In the RCs, statistics are used to evaluate and estimate the fields within [31]. In vehicles, volume sampling can be implemented with the random-walk technique.

The random-walk technique utilizes portable equipment, which offers quick, easy, and cost-efficient measurement procedures that can result to statistically stable results. In this paper, volume sampling is achieved with a continuously moved receiving discone antenna inside the vehicle. The antenna is moved inside the volume of the vehicle cabin in random locations and polarizations, therefore incorporating spatial alterations compared to the fixed position technique. The RTSA is simultaneously recording data in the same frequency range as with the discrete technique and for the same measuring time.

The two techniques investigated in this paper incorporate spatial and temporal properties of the EME differently [28]. The discrete, fixed position technique does not consider the spatial alteration effect, as it records the magnitude in a constant location over time by performing multiple sweeps over frequency. Oppositely, the random-walk technique assesses the EME changes over time, frequency, and space parameters [18] altogether. In Section III, both measurement techniques are compared and discussed.

III. RESULT ANALYSIS

For obtaining information about the internal and external environment of a vehicle and coming closer to an EME characterization, two techniques were applied incorporating different properties of the existing EME. An EME can usually be addressed via its four main parameters: time, frequency, space, and amplitude of the received signal. Both techniques applied here attempt an evaluation of the EME of a parked vehicle as discussed in Section II. The results of the discrete and random-walk methods are presented and additionally compared in this section. Moreover, a discussion on the usability of the different approaches via statistical tools in the future is made.

The main advantage of the RTSA for these EME measurements is that it has faster sweeping operation of the spectrum compared to a conventional SA [28]. Therefore, the issue of large sweep times of a traditional SA is alleviated [18]. Also, since many more sweeps can be recorded within the same time frame, a considerable number of samples per measurement is available for statistical processing. The frequent sweeps give the advantage of increased probability of capturing transient effects as also seen in Fig. 1. The figure shows 408 sweeps in the frequency range of 400 MHz to 500 MHz. Although the effective sampling rate per frequency point is around 145 ms, which might not be sufficient to register the very fast transients of digital signals, it’s a significant improvement over SAs [28] and can still successfully observe transients in a statistical manner. Ideally, the whole spectrum should be registered simultaneously with a very high sampling rate satisfying the Nyquist requirement for envelopes of all the present frequency components, but that is very difficult to achieve without expensive and bulky setup. As also shown in [29], spectrograms produced from time-domain receivers as e.g., oscilloscopes can describe an EME very well. The RTSA, on the other hand, can only generate a spectrogram within a comparably narrow frequency range (typically 30-180 MHz), but under the assumption that the EME did not significantly change within the sweep time of around 145 ms. A figure similar to a spectrogram can be generated for the sake of representing the EME behavior.

A. *Fixed position technique*

The fixed position (FP) technique, as already mentioned, excludes the parameter of space alteration, while focusing only on time-variance and frequency content. Usually, EMI is caused by the high values crossing the immunity level for a certain duration of the electronic equipment. In laboratory conditions, the given SUT would be illuminated for a certain fixed amount of time, i.e., dwell time. However, in a real environment, the time variance of the surrounding sources is much more complex, therefore their time-variance investigation is of high interest. As also shown in [31], measurements of longer duration increase the chance of a higher peak value occurring. Fig. 2 depicts an example of the raw maximum data of three independent measurements taken at the fixed front (FS) and back (BS) seats at the same polarization of the antenna at different times. As also shown in the figure, the EME presents distinguishable differences, which are a result of multiple parameters co-existing together making the EME random and complex. However, the magnitude measurement results obtained for each frequency point, as perceived by the receiver, are affected by the changes in the dimensions mentioned previously, both space and time. Furthermore, as seen in Fig. 2, the appearance of the peaks is distributed throughout the various performed measurements proving the high dynamics of the complex EME. As it is observed, each measurement presents a different occurrence of peak values, at different times. Since the appearance of these values cannot be assured while conducting such measurements, there is need for a more robust way to find them e.g., by estimating them from the available data.

Via the multiple sweeps of the RTSA, a depiction of the time, frequency as well as amplitude parameters obtained with the fixed position technique can all be shown in the same graph. As discussed in the previous subsection, the graph is not an actual spectrogram due to setting limitations of the RTSA. However, it gives a good estimation of the EME of the vehicle. The independent fixed positioned measurements are shown in the frequency range of 650 MHz to 850 MHz with 408 sweeps over time with the antenna placed at the front seat with vertical polarization. This depiction already offers wide information of the EME in the time and frequency domain simultaneously. The spectrogram of those data is presented in Fig. 3, showing that some of the frequency components are static, while the others, e.g., around 800 MHz, possess a strong time-variant behavior. Since each frequency component is measured individually, these data present the exact behavior of the time-variant components affecting the victim in that spot. This information can be used to address the probability aspect of a risk of EMI, following the risk-based EMC approach. So, following the fixed position technique, we can extract information regarding specific locations inside or outside a vehicle, creating thus a conclusive perception of the EME. This technique, however, does not address the severity properly, hence the random-walk technique is also applied and examined in the next subsection.

B. *Random-walk technique*

For the random-walk technique, as also mentioned before, the discone antenna was moved continuously inside the vehicle's cabin in different locations and polarizations. This results in a much stronger measured power variation, as shown in Fig. 2, due to the combined randomness of the time-variance and spatial distribution. Correspondingly to Fig. 3 of the discrete method, Fig. 4 depicts a spectrogram regarding the random-walk technique. In Fig. 4, the values are more variant compared to the fixed position technique from Fig. 3. These differences between the two graphs can also be seen more clearly from the red dashed area. As it can be observed, the fixed position results show the pure time-variance effect in contrast to the random-walk technique results. This response is due to the random-walk technique also incorporating the parameter of space alteration, which plays a significant role in a reverberant space such as the vehicle's cavity. One of the additional advantages of the random-walk technique is also the fact that it can produce statistically repeatable results due to the spatial alterations combined with the time variance. Since the receiver is moved through space over time in the random-walk technique, the behavior of the measured data is also time-variant yet yields more information. This way, it can estimate crucial values that could cause an EMC issue addressing thus the severity parameter of a potential EMI threat. Such a characteristic, though, is not accounted for in the fixed position technique. Therefore, it can be mentioned that each technique offers certain information on the EME in a different matter. Use of one or also combination of both can help come to understand and characterize real EMEs. It should also be mentioned that the two spectrograms, here, give an initial picture on some of the characteristics of each method but they do not represent a clean comparison between the two methods. As it will be discussed later in the paper, such an investigation needs multiple data sets as well as long measuring procedures and it is scheduled for future research.

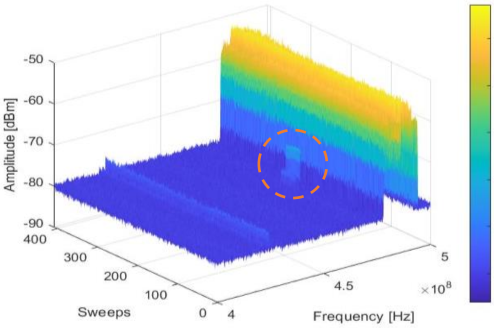

Fig. 1. Example of capturing transient effects over time via multiple sweeps using the RTSA.

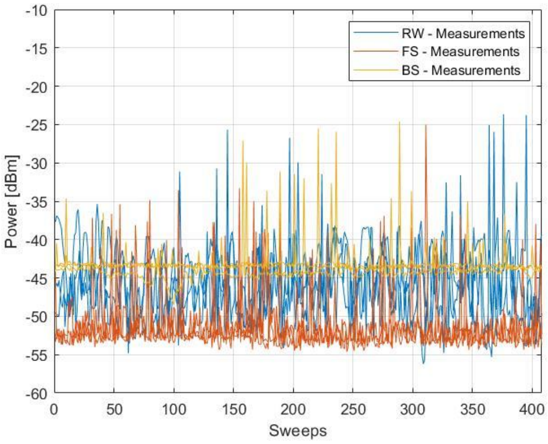

Fig. 2. Raw data of three measurements w.r.to time obtained with the fixed position technique in two different positions inside the parked vehicle as well as with the random-walk technique.

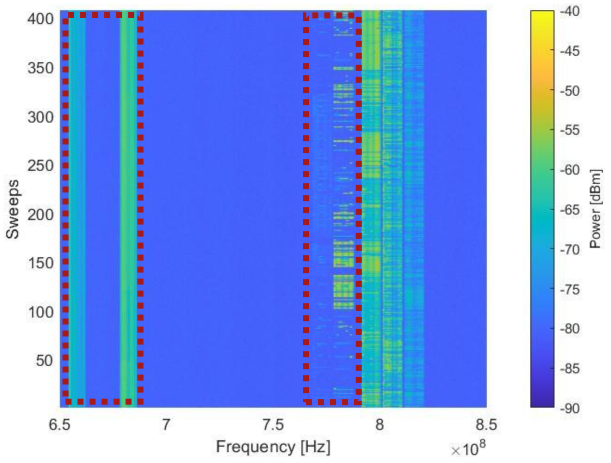

Fig. 3. Spectrogram showing the properties of each measurement in the frequency range of 650 MHz to 850 MHz using the fixed position technique.

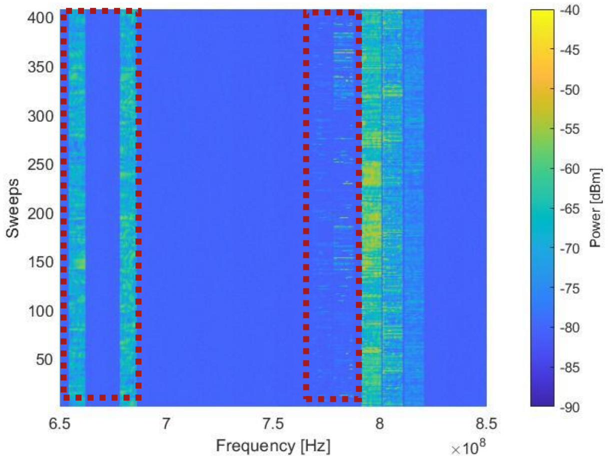

Fig. 4. Spectrogram showing the properties of each measurement in the frequency range of 650 MHz to 850 MHz using the random-walk technique.

IV. APPLICATION TO RISK-BASED EMC

As also shown in this paper and in [31], the recording of the maximum values is difficult to be achieved due to their low probability of occurrence as well as the very high unpredictability of the environment. As also shown in [11], any complex EME presents a number of known but also unknown sources creating an unpredicted and difficult-to-define environment. For example, our parked vehicle, can be threatened by a crucial field value that could couple from a certain angle or direction. To address such a case, we need to come closer on estimating real EMEs. Of great help, can be the statistical tools, such as Monte Carlo simulations and Bayesian Networks. Performing such a risk-based EMC analysis, we can then come closer to define the most critical parameters in an EME that could potentially cause some type of EMI to our system. As already proposed in [11], probability distribution functions (PDFs) can be applied to represent the various existing parameters of such an EME. As mentioned, usually EMI is caused from the maximum occurred values that couple onto a system. Therefore, their investigation and statistical behavior can help to estimate and predict how they will affect an intended operation. An example is shown in Fig. 5. In the figure, the distributions of maximum values of independent measurements using the fixed position technique as well as the random-walk technique are shown. As observed, the distribution of data regarding the fixed position measurements differs noticeably between the FS and the BS, indicating the strong effect of measuring in different positions and how a small change can cause a strong deviation to the final results. Both the data of the FS and BS positions seem to be concentrated in a small value span compared to the more widely distributed data of the random-walk technique.

The registered signal strength can be high due to its time-variant properties, successfully measured with a fixed-position measurement, but the car chassis additionally modifies this field due to the internal modal structure. Therefore, a chance exists that the field would be significantly higher or lower, depending on whether the antenna was located in a hot or cold spot, respectively. This issue is alleviated by applying random walk, which effectively sweeps through space and eliminates this issue. The random-walk technique might be adding the spatial alteration parameter making the analysis of each parameter challenging, but it can produce repeatable and stable statistical data, compared to the fixed position technique. However, by continuously performing a measurement in a different point in space, the actual representation of the time-variance is somewhat sacrificed in terms of defining the probability parameter for the risk-based EMC approach.

These types of distributions can be plotted for every selected frequency w.r.to the measurement time (sweeps) so that more information can be given for each characteristic of the EME. Therefore, crucial frequencies can be detected. Then, from the various PDFs, possible EMI threats could be identified and further overcome using tools such as the link-budget analysis and Monte Carlo simulations as proposed in [11]. Additionally, probabilistic models as e.g., Bayesian Networks, can use these values to estimate various incidents as well as predict worst-case scenarios, to minimize the risk of EMI.

To apply the proposed statistical analysis via the use of PDFs, a great number of independent and identically distributed (i.i.d) samples is needed to be obtained. For this goal to be achieved, volume sampling can be applied as shown. This technique can also be implemented via the discrete measurement technique, but it is not applied in this paper. However, such an examination is planned for future research. For application of this method, the receiving antenna needs to be placed in multiple different positions inside the car for long measurement times to obtain a great amount of useful data to perform statistical analysis [32]. Oppositely, the random-walk technique overcomes this limitation as it directly applies volume sampling offering multiple samples with ease.

Both measuring techniques seem to offer a set of useful data. The fixed position technique assesses an environment from discrete points in space, as it would have been seen by a victim as e.g., cable, sensor, etc. Therefore, information about the probability of occurrence can be obtained. On the other hand, the random-walk technique adds the space alteration parameter, which is not what the victim would normally be exposed to. However, this technique can be useful for detection of the worst-case scenarios. A good solution would be to obtain the PDFs from the discrete method, and via the random-walk scale it to fit the worst-case scenario.

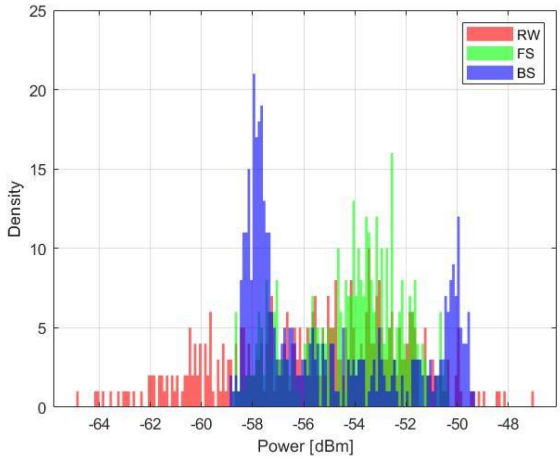

Fig. 5. Distributions of maximum values in the frequency range of 650 MHz to 850 MHz of three measurements with the discrete method in the front (FS) and back (BS) seat with same polarization of the antenna as well as with the random-walk (RW) technique.

In this subsection, only a brief discussion concerning the two measurement techniques and their response is given without extended analysis. Further investigation towards a comparison of the two methods is planned for future research. Additionally, incorporation of other parameters such as e.g., operational modes of the car, are also scheduled for investigation and representation via PDFs as presented in [11].

V. CONCLUSION

The complexity in automotive EMEs requires a more conclusive estimation towards real environments so that possible EMI threats can be detected and overcome. The effects of temporal and spatial configurations, as seen from this paper, play an important role while conducting EME evaluation measurements. Distinct measurements or fully detailed models do not seem to be helpful due to the randomness and unpredictability of the latter. Therefore, statistical analysis is proposed to incorporate the multiple parameters of the EME via the use of PDFs. Good estimation of the PDFs can be accomplished via volume sampling applied by the two methods presented in this paper. The random-walk technique seems like a proper solution to obtain the appropriate data. However, further investigation on the sampling and utility of the data for both measurements need to be done so that a conclusive comparison can be achieved. After good estimation of the values, probabilistic tools can be used to minimize the risk of EMI.

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