A Novel Segmentation Approach for Modeling of Radiated Emission and Immunity Test Setups

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Abstract—A novel procedure is developed to simulate radiated emission (RE) and immunity scenarios using a common approach for electronic control unit with complex wiring harness and terminations. This is possible by applying Huygens principle and Reciprocity theorem to the problem. A segmented approach is proposed to split the device under test into multiple segments, which converts the radiation problem to circuit simulation, in addition to reducing the requirement of computing resources. The proposed method is validated using measurements and also full-wave three-dimensional simulations for both RE and immunity test setups.

Index Terms—Automotive, electromagnetic compatibility (EMC), EM simulations, CISPR 25, Huygens surface, ISO-11452, radiated emissions (REs), radiated immunity (RI).

I. INTRODUCTION

GROWING competition in the automotive industry demands the development of new features and functionality with cost effective solutions and short design cycles. This leads to increased complexity of electronics and hence increased likelihood of Electromagnetic Compatibility (EMC) issues. Simulations based on accurate source and victim models allow us quantitative prediction for real EMC measurement/test environments. This paper illustrates a simulation method that provides a more efficient approach to the component radiated emission (RE) and immunity related predictions in a standard test setup [1], [2].

An RE test setup comprises a device under test (DUT) mounted over a metallic reference plane, together with a nearby receiving antenna. Typical DUTs contain ECU, cable harness, and terminations (loadbox) as shown in Fig. 1. The problem space may contain geometry features as small as 60 µm and a metallic reference plane, together with a nearby receiving antenna. Typical DUTs contain ECU, cable harness, and terminations (loadbox) as shown in Fig. 1. The problem space may contain geometry features as small as 60 µm and 60 µm in the ECU or as long as 1.7 m for the cable harness. EMC simulations for the entire test setup with a complex DUT are not possible using existing either time or frequency domain techniques on a workstation computer like HP Z820. Surface-based methods like method of moments [3], [4] can handle most of the modules, but are not practical in simulating a complex PCB, and a complex harness. Volume-based methods like finite element, finite integration technique, and finite difference time domain [3], [5] are suitable for complex PCBs but require huge computing resources for electrically large test setup environments with complex PCB and harness. Although hybrid methods can handle both DUT and test setup efficiently, they still need to handle large coupling matrices between the two domains, which again demand huge computing resources for this kind of problem [3], [6]. Moreover, the stochastic nature of the harness requires more than 20 harness variations to predict the statistical behavior of harness to compare with measurements [7], [8]. Due to the limited computing resources which exist on the workstation computer, complete simulation using three-dimensional (3-D) full-wave modeling of all parts in ECU and test setup is not practical. Therefore complex test setups could beneficially be divided into segments where each segment can be modeled using most appropriate and efficient techniques [3].

A more efficient method was proposed in [9] for handling CISPR-25 test setups. In this approach, radiation from DUT is involved and hence the problem is divided into two parts: interior and exterior regions using Huygens Equivalence Principle [9]. Solution to the exterior problem consists of generating an antenna transfer function using commercially available EM tools, where the transfer function’s input is a closed surface around ECU, harness, and loadbox. The exterior problem needs to be solved only once per antenna orientation and can be used for different DUTs as long as the test setup is based on CISPR-25. As shown in Fig. 1, in practice, a DUT contains three different types of modules: 1) ECU, 2) cable harness, and 3) loadbox. Physical size of these three modules will be different, as ECU is mostly cuboid, cable harness is 1.7 m long, square parallelepiped structure with small cross section, and the loadbox, in general, is complex and takes a rectangular parallelepiped structure. It may not be optimal and practical to place all of these elements
under one Huygens surface. To take advantage of these different shapes and volumes, it is proposed to divide further.

A three-domain segmentation is proposed in this paper and Fig. 2 shows such a split for a RE or immunity setup shown in Fig. 1. The split is done for the DUT where electrical connection exists. Here each domain is represented by computed $S$-parameter block, which also include one antenna port for each polarization or orientation. This is a unique representation compared to earlier paper [9], which enables reducing the radiation problem to circuit simulation and can be used for both emission and immunity simulations. In a system level simulator, each of the $S$-parameter blocks is combined along with appropriate source/emission models to determine the antenna voltage.

This paper extends the method provided in [9] and the main contribution of this paper includes: 1) extension of proposed approach to generic radiation problem by extending the $S$-parameters with additional antenna ports, 2) three-domain approach by splitting the interior region into three segments or domains, 3) demonstration of the approach to the radiation problems for both emission and immunity types, and 4) an efficient simulation method for the cable harness.

Section II will provide the procedure to generate $S$-parameters with additional antenna ports for DUT-to-antenna coupling by considering the interior problem as a whole one problem space. The proposed three-domain segmentation is also discussed. This method is validated using 1-m long wire in Section III. In addition, Section IV provides an efficient solution for the cable harness and demonstrates that different methods can be applied to each domain. In addition, the method is applied to radiated immunity (RI) problem and validated with measurements in Section V. In this paper, all 3-D EM simulations are performed using CST Microwave Studio (MWS) [10].

**II. METHOD DESCRIPTION**

In this section, the detailed procedure is provided to simulate the entire CISPR-25 RE test setup with DUT by solving the two regions independently, interior, and exterior. The method provided here can be used for other global standards and products as well.

**A. Formation of Huygens Surface**

Huygens equivalence principle is used to divide the entire simulation domain into two regions: Interior and Exterior. The interior region consists of DUT over the ground plate and the exterior region contains the entire radiation emission setup excluding the DUT. In this way, one can optimize existing resources to solve the complex problems. In addition, the entire test setup without DUT can be discretized in the commercial 3-D EM simulators without fine mesh/grid and can be simulated using workstation computers.

Consider the Huygens surface $\Gamma$ to enclose all EM sources as shown in Fig. 3(a). This surface splits the entire space into interior and exterior regions. It is required to determine surface currents on this surface using enclosed EM sources and then find the antenna voltage. This is called forward solution [9] and the fields on this surface $\Gamma$ can be computed using 2-D/3-D numerical methods or using commercial tools. But, the exterior problem which contains surface currents defined over several thousands of grid points on the Huygens surface and determining the antenna voltage for each current source on the Huygens surface is not practical. Instead, one can use the reciprocity theorem [9], [11], and obtain the reverse solution as shown in Fig. 3(c). In this case, antenna is excited with known voltage level and one 3-D EM simulation run is sufficient to determine the unknown surface currents on the Huygens surface. The simulation space contains only antenna and reference ground plate. The reciprocity theorem will be used to combine both forward and reverse solutions [9].

**B. Antenna Transfer Functions**

The antenna transfer function has been generated by using a terminal voltage, $U^{TF}$ at the antenna port in 3-D simulations. The entire region shown in Fig. 3(c) is simulated and captured the electric and magnetic fields over the Huygens surface. These computed fields are used to generate the surface currents on the surface $\Gamma$ using the following expressions:

$$J^{rev} = n \times H^{rev}$$  \hspace{1cm} (1a)

and

$$M^{rev} = E^{rev} \times n$$  \hspace{1cm} (1b)

where $E^{rev}$ and $H^{rev}$ are electric and magnetic fields on the surface due to antenna illumination and “$n$” is a unit vector defined as outward normal on the Huygens surface, $J^{rev}$ and $M^{rev}$.
\[ M^{\text{rev}} \] are electric and magnetic currents on the Huygens surface, respectively. These surface currents are used to form the antenna transfer function as given below:

\begin{equation}
F_j^{\text{rev}} = -\frac{S_A}{U_a^{\text{fwd}}} J_j^{\text{rev}} \quad \text{and} \quad F_M^{\text{rev}} = \frac{S_A}{U_a^{\text{fwd}}} M^{\text{rev}}
\end{equation}

where \( S_A \) is surface grid area on the Huygens surface. Equation (2) describes the partial transfer function associated with a surface current in a particular element on the discretized Huygens surface due to the antenna excitation. The near-field distribution based antenna transfer function contains the specific behavior of test setup including ground reflections, antenna detuning due close proximity to ground plane and metallic table, and structural resonances. The reverse solution as illustrated in Fig. 3(c) allows us to extract the antenna transfer function using only one simulation run without DUT.

**C. Antenna Voltage**

The current at the antenna port (\( I_{\text{ant}} \)) can be computed using the reciprocity theorem [11] due to the fields \( E^{\text{fwd}} \) and \( H^{\text{fwd}} \) from the forward solution as shown in Fig. 3(b). The following equation for induced current at the antenna port can be derived as shown in [9]:

\begin{equation}
I_{\text{ant}} = F_M^{\text{rev}} \cdot H^{\text{fwd}} + F_j^{\text{rev}} \cdot E^{\text{fwd}}
\end{equation}

where \( F_M^{\text{rev}} \) and \( F_j^{\text{rev}} \) are the antenna transfer functions for the given test setup. The antenna voltage at the port can be computed using the following equation:

\begin{equation}
U_{\text{ant}} = Z_{\text{ant}} I_{\text{ant}}.
\end{equation}

In the case of biconical antenna, there exists a feeding balun, which transforms the 200 to 50 \( \Omega \). In such a case, a simple impedance transformer is implemented and the antenna voltage can be determined as:

\begin{equation}
U_{\text{ant}} = \sqrt{Z_g Z_{\text{ant}}} I_{\text{ant}}
\end{equation}

where \( Z_g \) is the generator impedance.

**D. Antenna Ports for S-Parameter Block**

\( S \)-parameters of the DUT can be obtained using 3-D EM simulations. It is required to extend the ports of the DUT to incorporate the antenna port voltages as shown in Fig. 4. Extended \( S \)-parameters can be formulated using (4) and (5) as provided below:

\[ S = \begin{bmatrix}
S_{11} & S_{12} & \ldots & S_{1N} \\
S_{21} & S_{22} & \ldots & S_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
S_{N1} & S_{N2} & \ldots & S_{NN}
\end{bmatrix}
\]

where

\[ S_{\text{ant},i} = b_{\text{ant}} \sqrt{a_i} \quad a_n = 0, \quad n \neq i, \quad b_{\text{ant}} = \frac{U_{\text{ant}}}{\sqrt{Z_0}} \]

\( U_{\text{ant}} \) is antenna port voltage \( (4) \), \( Z_0 \) is antenna port’s reference impedance (chosen as 50 \( \Omega \) to represent the impedance of the measurement system), and \( S_{i,j}, i, j = 1, 2, \ldots, N \) are the \( S \)-parameters of the DUT. The antenna port’s reflection coefficient can be used to fill the \( S_{\text{ant},\text{ant}} \) parameter. This parameter can be obtained from the simulations performed for the exterior problem with the RE test setup. In this way, the extended \( S \)-parameters with antenna port include the specific test setup characteristics along with the DUT’s behavior including the resonances and coupling between them.

Similarly, one can add two antenna ports, one for horizontal and the other for vertical orientation of the antenna. These ports are fully decoupled to each other to represent the two independent antenna measurements. This is a useful approach as these \( S \)-parameter blocks can be simulated in system or circuit simulators. Intended ports of DUT can be excited with noise sources. The predicted antenna voltages in the circuit simulator provide the RE levels in terms of antenna voltages. One can transform these antenna voltages to field values using antenna factors, which can be obtained from simulations or measurements. Moreover, this method provides a means to study RI scenarios by exciting the antenna port with an appropriate voltage to generate the target threat field level. Furthermore all features of circuit simulators like sensitivity analysis and also optimizations of component values (e.g., for filter improvement) are directly usable with this formulation on a simple workstation computer.

**E. Three-Domain Approach**

The procedure described so far is useful for simple DUTs like sensors that contain two or three wires and a small size PCB. It is difficult to keep typical automotive ECUs like electronic stability program (ESP) and complex harnesses within the interior region as computational requirements are high. In this section, three-domain segmentation is applied to the interior problem.

Consider a simple DUT split into three parts. For example, a 1-m long wire is divided into three domains and the corresponding Huygens surfaces are shown in Fig. 5. At the cut-away interface, waveguide ports are used on both sides to emulate continuous flow of current in both forward and backward directions. These ports are defined with respect to the characteristic impedance of the wire cross section. This is very important, because the waveguide ports are excited with known incident wave \( a = 1 \), and hence all the fields obtained are referenced to
the characteristic impedance of the respective wire or port only. In this approach, the interface between the domains has been chosen in a way that homogeneous TEM mode exists on either side. This will minimize the influence of the split on the results. Normalization is applied on the $S$-parameters after the creation of antenna ports [12].

The extended $S$-parameters may be used to predict EMC performance characteristics. For example, emission related simulation may be represented as shown in Fig. 6. In this case, emission source is applied to the internal port of Domain 1. This source drives the simulation and antenna voltages can be obtained. These complex voltages are combined to generate the antenna voltage at the respective antenna port as follows:

$$U_{\text{ant}} = U_{\text{ant}}^1 + U_{\text{ant}}^2 + U_{\text{ant}}^3.$$  \hspace{1cm} (7)

Only the sum of the complex voltages has physical meaning whereas the individual voltages may support debugging issues in EMC. In a similar way, one can predict the induced voltages and currents at the desired component pins or ports using the same set of $S$-parameters for the case of RI simulations. In this case one needs to calibrate the power fed to the antenna to the desired field strength. This process is demonstrated in Section IV. In this way, one can incorporate the $S$-parameter blocks in system level simulations to optimize the circuit to reduce the EMC effects. The next section describes the implementation and validation of the three-domain approach.

III. VALIDATION OF THE APPROACH

In this section, a 1-m long wire is used for validation of three-domain approach as shown in Fig. 5. Both measurement and reference 3-D full-wave simulations are used for this purpose.

A. Measurement Setup

Measurements are carried out in a CISPR-25 compatible chamber to validate the proposed approach. All the measurements are carried out using the setup shown in the Fig. 7. A single wire is considered here with diameter of 1 mm. The setup includes the opto-link module that converts RF signals near the port 1 (one end of wire) and transmits the data over the fiber cable to the opto coupler module, which converts back to the RF signal. This signal is fed to the network analyzer for $S$-parameter measurements. On the other side, the antenna port is directly connected to the network analyzer at port 2. In this way, wire/antenna coupling to the feeder cable is avoided.

Fig. 8 shows the actual test setup in the chamber with biconical antenna. All the cables used in the setup and opto-link are calibrated prior to the measurements. The transmission coefficient ($S_{21}$) between the antenna and wire port is measured using the network analyzer.

B. 3-D Full-wave Simulation Setup for Reference

As we prepare the simulation model for test setup, it is required to discuss the potential errors introduced by the model. It was well demonstrated that both the size of the table and the way the table is grounded influence the fields measured by the antenna [13]–[16]. Kriz and M"ullner [13] and Warkentin et al. [14] reported that the setup can resonate in the frequency range 10–50 MHz, and hence the actual test setup needs to be considered along with the grounding mechanism and loading of complex absorbers. For this purpose, the Absorber Lined Shielded Enclosure is simulated using the ferrite and dielectric layers along with the spacer backed with metal wall as shown in Fig. 9. Material properties are optimized for complex absorber reflectivity [16], [17]. Chamber size is kept as it is in the simulation to make sure that proper reflectivity is maintained within the chamber. If one uses absorbing boundary condition like perfectly matched layer, then the reflectivity of the chamber walls is neglected and hence simulation results may not be comparable to that of the measurements.
In addition, it is difficult to emulate the table top connection to the chamber wall through ferrite tile lining that poses higher impedance to the ground plate without proper chamber model [16].

C. Implementation Details

Huygens surfaces are discretized with Cartesian grid with 20 mm in each direction for the simulation up to 300 MHz. This grid is chosen to have a sufficient number of grid points along the cross section of Huygens surface. All the interfaces were simulated using waveguide ports with 400 mm × 200 mm for proper excitation. Even though larger port sizes are better, but increases the simulation time significantly for computing the port modes when a large number of conductors is considered. The DUT is discretized with 0.5 mm grid for the wire cross section and 5 mm along the length of the wire. The rest of the space is discretized with 30 cells per wavelength. Termination criteria for all the simulations are chosen to have −60 dB energy decay from the maximum for split solutions and −50 dB for generating the antenna transfer functions.

D. Validation of the Approach

It is required to validate the simulation model of the antenna and chamber in CST MWS [10]. Fig. 10 shows results for both horizontal and vertical orientations of antenna. It is observed that the measured results and reference simulation results without split have very good agreement. It is emphasized here that proper termination of chamber walls and table ground plays very important role when one tries to compare the measured results with those of simulation results [16].

To validate the three-domain approach, antenna transfer functions are generated using CST MWS for biconical antenna in the frequency range of 1–300 MHz [18]. DUT is split with 250 mm (Domain 1), 500 mm (Domain 2), and 250 mm (Domain 3), as shown in Fig. 5. The 3-D EM simulations are carried out for each domain to obtain the surface fields and S-parameters. Each of these S-parameter blocks is combined in the circuit simulator to obtain the antenna voltages for each domain independently. Actual currents existing on the interface ports between the domains will determine the antenna voltage contributed by each domain. All the complex antenna voltages are added together and normalized to the excitation voltage to obtain the transmission coefficient for the wire to the antenna. Results for the split approach are also shown in Fig. 10. Good agreement is observed between the three-domain approach and 3-D simulations for both horizontal and vertical polarizations. These results validate the proposed split approach. In this way, the interior problem can be divided into three small 3-D EM simulations, which can be solved quickly because of smaller volume and matched interface ports.

IV. MULTICONDUCTOR TRANSMISSION LINE METHOD FOR DOMAIN 2

The proposed segmentation approach enables one to solve each domain independently by a suitable method [3]. Harnesses can have a minimum length of 1.7 m as per CISPR25 [1] requirement and more than 50 wires for typical ESP applications. It is not practical to solve this problem using 3-D EM simulations. Only viable option in this case is the MTL theory [19].

A. Approach

In this section, a simplified method is provided for the middle domain (Domain 2) that contains the cable harness only. The harness might contain twisted pairs and different cross sections of wires for power supply, motor supply and also control/data signals. It is well known that most REs from harnesses are due to common mode (CM) current flow in the harness. From the EMC point of view, all the critical wires are in most cases...
twisted pairs, and differential current radiation through these twisted pairs can be neglected when compared to the CM current emissions. Here MTL method is provided as an alternative to 3-D EM simulations for Domain 2 considering only radiation due to CM currents.

\[ S \text{-parameters can be computed for a given harness cross section using Fourier method described in [19] and using transmission line theory. Alternatively, one can also use any commercial solver for computing the S-parameters. The outwards traveling waves can be calculated assuming an excitation at port "i" and all other ports are terminated with 50 \Omega. Port voltages and currents can be determined as follows:} \]

\[ U_n = \sqrt{Z_0} (a_n + b_n), \quad I_n = \frac{(a_n - b_n)}{\sqrt{Z_0}}, \quad a_n = 1, \quad n = i \]
\[ a_n = 0, \quad n \neq i \quad (8) \]

\[ b_n \text{ values are computed using S-parameters of the harness. From these port voltages and currents, the CM voltage and current levels at the beginning and end of the harness are computed using the following equations [10]:} \]

\[ U_{CM1} = \frac{1}{N} \sum_{n=1}^{N} U_n, \quad U_{CM2} = \frac{1}{N} \sum_{n=N+1}^{2N} U_n \quad (9) \]
\[ I_{CM1} = \sum_{n=1}^{N} I_n, \quad I_{CM2} = \sum_{n=N+1}^{2N} I_n \quad (10) \]

where \( N \) is the number of wires in the harness.

The characteristic impedance and propagation coefficient can be determined from the harness cross section for CM approximation using the methods described in [19]. The current on the CM wire is decomposed into forward and reverse currents for computing the actual current, which exists on the wire as shown in Fig. 11. The entire harness is divided into a certain number of sections and the dipole formulae can be used for each section to calculate the electric and magnetic fields using the harness current in respective section. The total field on the domain surface can be computed by summing up all current section contributions. In this way, for Domain 2, which contains only the cable harness, forward fields can be computed and hence antenna voltage using the antenna transfer functions as described in Section II.

The CM current segment is extended beyond the domain interfaces on both left and right sides as shown in Fig. 11. This is required to make sure that continuous currents on the wire produce continuous fields on the surface. For this application, 1-m extended line length is used to assure the field continuity at the domain interface.

## B. Validation of the Approach

To validate the proposed MTL method for the cable harness, a test setup using CISPR-25 standard is built as shown in Fig. 12. Here a heat-sink [20], [21] with a two wire harness is considered with the PCB at one end as described in Fig. 13 and an LISN with two ports at the other end (Supply, Ground). The dimensions of the heat sink were taken from [20] and insulator thickness is 1 mm. FR4 substrate of 1.6 mm is used for this simulation with dielectric constant of 4.8 and loss tangent of 0.02. The two wire harness is used with a radius of 1 mm for each wire and the center-to-center distance between the two wires is 4 mm. internal port assignment is shown in Fig. 14. Insulating material is used to isolate the heat sink with PCB ground and also with the MOSFET pad. One discrete port is created for inserting the ac signal at the MOSFET and two discrete ports are used near the connector region for inserting the input filter (1 \( \mu \)H in series and 20 \( \mu \)F in shunt configuration) as shown in Fig. 14. As per CISPR-25, 1.5 m separation between the bent wires is considered. It is required to generate the antenna transfer functions for each orientation of the antenna and for each Huygens surface as shown in Fig. 12—red for Domain 1, green for Domain 2, and blue for Domain 3. The procedure is similar to the one discussed in Section II, and the 3-D EM simulator is used to obtain the antenna transfer functions. In this case, a log-periodic antenna in the 200–1000 MHz frequency range [22] is considered. These
antenna transfer functions are computed only once and can be reused for all the simulations as long as the DUT modules fit in the predefined Huygens surfaces.

A split is done for the middle domain (Domain 2) with a length of 1.22 m and the remaining parts of harness are placed in Domain 1 and Domain 3. Three different sets of simulations are performed for this validation: 1) 3-D CST MWS Simulations for the complete test setup with DUT as a reference simulation, 2) all the split domain solutions are performed with CST MWS, and 3) Domain 1 and Domain 3 using CST MWS and Domain 2 solution is obtained using the MTL method. MTL method is used to compute the CM current on the harness using S-parameters for the cable harness section in Domain 2 and the dipole approximation is used to compute the forward electric and magnetic fields on the Domain 2 surface. All three S-parameter blocks with antenna ports are simulated in the CST Design Studio for 1 Volt excitation at the contact point of the MOSFET as shown in Fig. 14. The LISN circuit provided in [1] is used for terminations of two wires in Domain 3. Circuit simulation provides three voltages for each orientation of the antenna. All three of them are added to get the antenna port voltage for the respective orientation.

Huygens surfaces are discretized with Cartesian grid with 10 mm in each direction for the simulation up to 1000 MHz. All the interfaces were simulated using waveguide ports with 400 mm × 200 mm for proper excitation. The DUT is discretized with 0.5 mm grid for the insulating material and also for wire cross section and 5 mm along the length of the wire. The rest of the space is discretized with 30 cells per wavelength. Termination criteria for all the simulations are chosen to have −50 dB energy decay from the maximum for all the simulations.

The proposed three-domain approach is validated for a log-periodic dipole antenna as shown in Fig. 15 for vertical orientation. Results based on the proposed approach are in good agreement with the reference simulations. There exist 3 dB deviations for vertical orientation from 650 to 1000 MHz, and these deviations are attributed to missing field interactions with vertical currents due to splitting in the other domain. The Domain 2 solution with MTL method is in good agreement with the corresponding solution using CST MWS. Results for horizontal orientation are provided in Fig. 16. Good agreement has been observed between the three-domain split approach and the full reference simulations except for the peak near 400 MHz for the MTL method. This method is found to be very useful for converting the radiation problem to circuit level simulation which will help in optimizing the EMC performance as desired.

Table I provides the simulation times required for each approach on a HP Z820 workstation. All the simulations are performed with the same level of grid resolution for DUT and antenna. CST Design Studio is used to perform the circuit level simulation using the extended S-parameter solutions. The three-domain approach reduces the required simulation time drastically by a factor 20. The demonstrated example is the extreme case which can be solved in this workstation, but simulation time is too high, 11 days, and not practical for EMC applications. The proposed approach reduces the simulation time drastically. If one considers a typical ESP with PCB along with
V. MODELING OF RI TEST SETUP

REs and immunity problems are reciprocal in nature. Hence, one can still use S-parameter blocks with antenna ports for predicting the induced voltage/power levels for the susceptible pins/locations. In this section, a horn antenna in the 1–3 GHz frequency range [23] is validated in the RI test setup using both measurements and the proposed approach. In this frequency range, intention is to illuminate radiation directly on the DUT by placing the antenna in front of the DUT. It is expected that ECU section of the DUT is most effective in 1–3 GHz frequency range, and hence, here only a single domain is sufficient for determining the induced voltage or power levels inside the DUT. Since the horn antenna is simulated with waveguide port, it is required to have an impedance transformer, as described in Section II.

Validation is performed for two test cases: 1) transmission coefficient between the horn antenna and wire ports and 2) received power at wire port under the constant field exposure by horn antenna.

A. Validation – Transmission Coefficient

To validate the transmission coefficient, a floating ground plate with short wire at 50 mm above the ground plate is used as a DUT shown in Fig. 17(a). The transmission coefficient between the antenna port and wire port is measured as shown in Fig. 17(b). Here again, opto-link is used to avoid the coupling between the cable and high gain antenna. Fig. 18 shows the measured and simulated transmission coefficients. Simulation results show very good agreement between them and validate the accuracy of the proposed method. These results are also compared against measured transmission coefficient and found close agreement except the frequency shift near 2 and 3 GHz.

B. Validation – Received Power at Wire Port

In the case of RI test, it is required to maintain the constant field strength as specified by the ECU level requirements. As per the ISO-11452-2 standard [2], field probe is required to keep at 150 mm above ground plane and at 1 m distance from antenna to calibrate the power required to maintain the field strength. Test setup used for calibration is shown in Fig. 19. This procedure will determine the required power levels to maintain the constant field strength at the probe/DUT location.

During the computation of antenna transfer function, field strength is also computed at the specified probe location for all frequencies of interest with 1 V source at antenna port. The computed field value is inverted to get the required antenna voltage for generating 1 V/m field strength. Computed voltage source data for generating field strength of 1 V/m is shown in Fig. 20 for the horn antenna and is stored in a database along with the VSWR of the particular antenna under consideration. This data is used to generate the required field strength and source multiplier will be used to generate the actual field strength using voltage controlled voltage source in the circuit/system simulator.

For validating the immunity source, RI test was performed with 10 V/m field strength specification. As defined in ISO-11452-2 [2], a field probe is used to calibrate the power level required for the given field strength. Calibration is performed at discrete frequencies with step size of 100 MHz as
the present setup with automated scan will observe only functional failures during the immunity test. Calibrated power is fed to the Horn antenna that is placed right in front of the DUT at a distance of 1 m. The received power at the wire port is measured and results are shown in Fig. 21. Reference simulation and split approach have been performed for this test setup using the voltage source shown in Fig. 20 to compute the received power at the wire port. Simulation results are also shown in Fig. 20 and good agreement is observed between them except near 3 GHz. In this way, one can simplify the RI problem to the circuit problem and can be used to optimize for EMI performance.

VI. CONCLUSION

A procedure for three-domain approach has been provided for RE and immunity problems. This approach provides $S$-parameter sets that include two additional antenna ports. The split approach has been validated using both measurements and 3-D full-wave simulations for the case of a 1 m long wire. Generated $S$-parameter blocks are combined in the circuit simulator and the emission levels with 1 V source at the ECU internal port are obtained. For typical EMC investigations, Domain 1 resimulation is sufficient for quantifying the EMC improvements if user has made structural changes for ECU, and circuit level simulation is sufficient for component changes. All the features of circuit simulators like sensitivity analysis and filter optimization are usable with this formulation. In addition, benefits of the method have been demonstrated using a CISPR-25 compatible setup in terms of simulation time. For RI applications, one can obtain the voltage/power at the internal ports using the calibrated voltage source for predefined field strength at the antenna port. The proposed approach has been validated for the frequency range of 30 MHz to 3 GHz.

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