Analysis of Radiated Emissions from FlexRay Automotive Bus Systems

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Abstract— **Due to the high data rates of FlexRay communication systems, EMC can be a big challenge. It is crucial to develop new and fast methodologies to evaluate electromagnetic disturbances. This paper focuses on the radiated emissions from FlexRay communication systems, which is mainly induced by common mode current on the twisted-pair cable. VHDL-AMS modeling language is employed to investigate common mode currents in FlexRay bus networks. An equivalent common mode radiation model of a twisted-pair cable above a reference ground plane is established by simplifying it into a single transmission line parallel to ground. Through combing common mode currents as radiation source by VHDL-AMS analysis with a simplified radiation model, efficient analysis of radiated emissions from bus networks is possible. The proposed fast approaches are an analytic method and a multiple-dipole method based on Green function and mirror theory. The radiated emissions from different topologies of automotive networks are analyzed and verified by full wave methods.**

Keywords-FlexRay; CAN; EMC; radiated emission; automotive bus systems; common mode current; VHDL-AMS

I. INTRODUCTION

FlexRay communication systems are a promising candidate to supplement or even replace some existing data buses due to higher data rates up to 10Mbit/s. This high data rate on the one hand can significantly improve several functions in automotive applications; on the other hand it inevitably leads to increased electromagnetic emissions level. In order to measure these emissions originating from the unshielded twisted-pair cables of FlexRay bus systems, radiated test standards like the ALSE method according to CISPR-25 can be used. Figure 1 shows the configuration of a point to point topology that represents the simplest bus network and can be considered as the basic element for more complex buses constructions. The high-speed differential signal, in practice, may be transformed into a common mode signal because of asymmetrical behavior of transceivers as well as the unbalance between the two differential signal paths [1]. The common mode current on twisted-pair cables is the main reason for electromagnetic radiated emissions. Too high radiated emissions may lead to expensive redesigns and cause seriously delays of a product launch. It is crucial to evaluate and predict EMC performance of a product in prior period. With respect to radiated emission prediction many full wave methods can obtain accurate results, such as FIT (Finite Integration Technology) or MoM (Moment Method). These methods, however, at the cost of consuming much time are usually non-preferable in practical application especially in evaluation of extended cable networks. Furthermore full wave methods face serious problems when dealing with non-linear circuits.

Therefore implementing new and fast methodologies to predict radiated emissions from automotive networks like FlexRay or CAN is necessary. VHDL-AMS, widely applied in many industrial fields, can be used to fill a number of needs in design processes. This paper employs this modeling language to analyze common mode currents in FlexRay networks that can be used as radiation source along a cable. In order to avoid full wave simulation methods, a so called analytic method [2] and the multiple-dipole method [3] are introduced to calculate radiated emission originating from a FlexRay bus system. Two fast methods are presented and verified by full wave methods in section II; in section III a VHDL-AMS circuit model of FlexRay point to point topology is constructed based on transmission line (TL) theory, and a simplified radiation model of a cable parallel to ground is presented. Radiated emissions from point to point topology and a passive topology are simulated in section IV. Finally the proposed methods are summarized in section V.
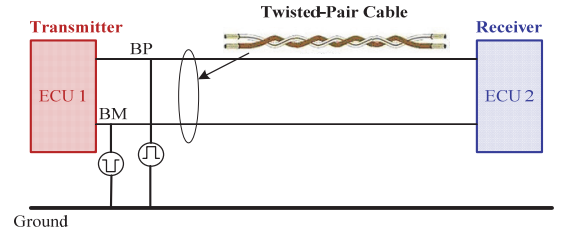

Figure 1. Point to point topology of FlexRay bus system

II. FAST METHODS FOR EMISSION MODELING

A. The analytic method

The so called analytic method from [2] is one approach to calculate near and far electromagnetic fields from a thin conductor (Figure 2(a)). For example, the x-direction $\boldsymbol{H}(t)$ and the y-direction $\boldsymbol{E}(t)$ are given by:

$$H_x(t) = \frac{-y}{4\pi}\left[I_0(t) + I_L(t)\right] \tag{1}$$

$$E_y(t) = \frac{-y}{4\pi\varepsilon_0 v_0}\left[\frac{F_0(t)}{R^3(0)} - \frac{F_L(t)}{R^3(L)} - \frac{z}{R(0)}I_0(t) + \frac{L-z}{R(L)}I_L(t)\right] \qquad (2)$$

$$I_0(t) = \frac{1}{\rho^2}\left[u(0,t-\frac{R(0)}{v_0})/Z_C + \frac{z}{R(0)}i(0,t-\frac{R(0)}{v_0})\right] \qquad (3)$$

$$I_L(t) = \frac{-1}{\rho^2}\left[u(L,t-\frac{R(L)}{v_0})/Z_C + \frac{z-L}{R(L)}i(L,t-\frac{R(L)}{v_0})\right] \qquad (4)$$

$$F_0(t) = C\int_0^t i(0,\tau - R(0)/v_0)d\tau \quad F_L(t) = C\int_0^t i(L,\tau - R(L)/v_0)d\tau \qquad (5)$$

Where $I_0(t)$, $I_L(t)$, $F_0(t)$ and $F_L(t)$ are the functions of nodal voltages and branch currents at both ends of the TL. ε_0 is the dielectric constant of vacuum, v_0 is the velocity of light in vacuum, Z_C is the characteristic impendence, L is the length of line, R is a distance function from observation point P (x, y, z) to any point on TL, and $\rho = \sqrt{x^2 + y^2}$. $u(0,t-R(0)/v_0)$ and $u(L,t-R(L)/v_0)$ are the voltages at beginning and end of the conductor; $i(0,t-R(0)/v_0)$, $i(L,t-R(L)/v_0)$ are the currents at beginning and end of the conductor. Above expressions including v_0 indicate that signal propagation velocity along the TL must be equal to speed of light. Therefore this approach is currently only implemented for TLs without dielectric coat, but in typical automotive configuration error can be expected low when dielectric coating is not considered.

B. The multiple-dipole method

The multiple-dipole method [3] subdivides a TL into a number of short dipoles (Figure 2(b)). The total radiated electromagnetic field is the sum of all contributions from each constituent dipole. For example, the x-direction **H**(t) and the y-direction **E**(t) of each dipole are given in Cartesian coordinates:

$$H_x(t) = \frac{-dL \cdot y}{4\pi}\left[\frac{1}{r^3}I(t-r/v_0) + \frac{1}{v_0 r^2}\frac{\partial I(t-r/v_0)}{\partial(t-r/v_0)}\right] \qquad (6)$$

$$E_y(t) = \frac{dL \cdot yz}{4\pi\varepsilon_0 r^2}\left[\frac{3I(t-r/v_0)}{v_0 r^2} + \frac{3\int_0^t I(t-r/v_0)d\tau}{r^3} + \frac{1}{v_0^2 r}\frac{\partial I(t-r/v_0)}{\partial(t-r/v_0)}\right] \qquad (7)$$

Where r is the distance from the dipole to the observation point P, ε_0 is the dielectric constant of vacuum, v_0 is velocity of light in vacuum, dL is length of Hertzian dipole. $I(t-r/v_0)$ is the current on the dipole of delay time $(t-r/v_0)$.

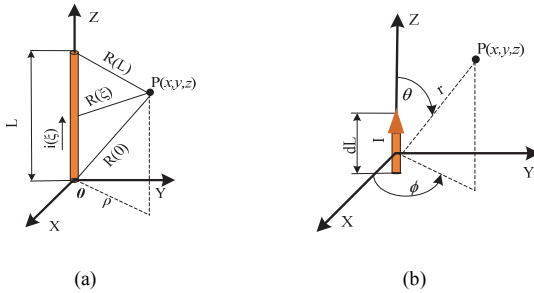(a)   (b)

Figure 2. Radiation model for analytic method and multiple-dipole method

C. Verification of the analytic and multiple-dipole method

For verifying the analytic method and the multiple-dipole method the radiated fields of a TL parallel to ground (as shown in Figure 3), using MoM method and FIT Method, are calculated and compared. We assume a time domain voltage source $V_s(t) = V_m e^{-\alpha t}\sin(\omega t)$ on the termination C_1, where $V_m = 10$, $\alpha = 4\times10^7$, and $\omega = 2\pi\times10^8$, and the resistance of termination C_2 is 50 Ω, the length of the TL is 1.5 m, the height of observation point is h=50 mm, and the distance to TL center of observation point is 0.15 m.
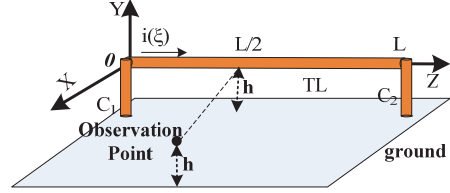

Figure 3. Radiation model setup of transmission line parallel to ground

When using the analytic method or multiple-dipole method to calculate the above radiation model, firstly TL theory is required in order to obtain the voltage and current distribution on it. Then the mirror theory is applied to deal with the reflection from ground. In Figures 4 and 5 the y-direction electric field and x-direction magnetic field at the observation point are shown.
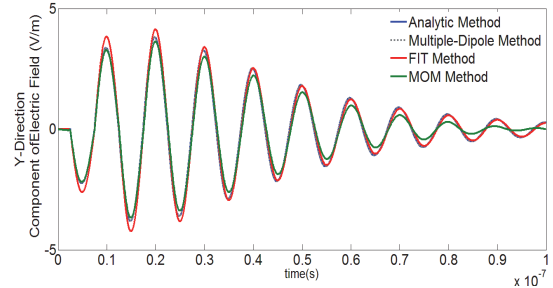

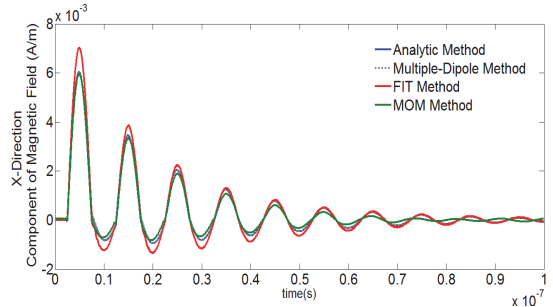Figure 4. The y-direction electric field at the observation point

Figure 5. The x-direction magnetic field at the observation point

The results of the analytic method and multiple-dipole method match very well with the other two full wave methods; but advantages of the analytic method are simplicity and short computation times when predicting radiated fields from a homogeneous TL parallel to the ground. The multiple-dipole method, compared to the analytic method, needs more computation time if the number of short dipoles is large.

III. MODELING A POINT TO POINT BUS SYSTEM TOPOLOGY

Point to point topology can be seen as the basic element for a FlexRay bus network, as shown in Figure 1. ECU is the acronym for "Electrical Control Unit" integrating a transmitter and receiver circuit; differential voltage is defined as the voltage between two signal wires (twisted-pair cable), denoted BP (Bus Plus) and BM (Bus Minus). Excepting twisted-pair cable, the bus system model actually contains transceiver, common mode choke and termination as shown in Figure 6.
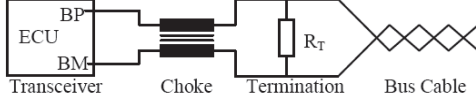

Figure 6. Typical components of a FlexRay bus system

A. The procedure for simplifying radiation models

As described above, differential mode voltage can be transformed to an unexpected common mode voltage mainly resulting from the non-synchronized driver signals at the BP and BM or other asymmetries in the termination and cable system. The non-synchronized driver scenario is considered in this paper. Figure 7 shows the procedure for simplifying a point to point bus system, which includes the following steps:

(a) Separating the differential and common mode voltages;

The differential mode voltage (V_{diff}) and common mode voltage (V_{comm}) can be defined by the voltages (V_{BP} and V_{BM}) on two signal wires of the twisted-pair cable:

$$V_{diff}=V_{BP}-V_{BM} \qquad V_{comm}=0.5\cdot (V_{BP}+V_{BM}) \qquad (8)$$
$$V_{BP}= V_{comm}+V_{diff}/2 \qquad V_{BM}= V_{comm}-V_{diff}/2 \qquad (9)$$

A schematic drawing is depicted in Figure 7(a); where the Z_{equ} is the equivalent impedance of receiver circuit termination.

(b) Constructing the model excited by common mode voltages;

The two single wires of twisted-pair cable are excited by differential voltage pairs ($V_{diff}/2$, $-V_{diff}/2$) and common voltage pairs (V_{comm}, V_{comm}). From the view of signal integrity, the voltage pairs ($V_{diff}/2$, $-V_{diff}/2$) also can be defined as odd-mode voltage; voltage pairs (V_{comm}, V_{comm}), on the other side, can be defined as even-mode voltage. When these two mode voltages travelling along the twisted pair wire, they face the different impedances that can be defined as odd-mode impedance (Z_{odd}) and even-mode impedance (Z_{even}) [6] respectively. Since odd-mode voltage and even-mode voltage are independent from each other, it is reasonable to establish the radiation model only excited by even-mode voltage as shown in Figure 7(b).

(c) Simplifying common mode voltage sources;

In Figure 7(b), two single wires of a twisted-pair cable are excited by the same common mode voltage V_{comm}, thereby the voltage sources can be simplified to one single exciting voltage source, as shown in Figure 7(c).

(d) Establishing an equivalent radiation model.

In order to calculate radiated fields from the twisted-pair cable, the equivalent TL is established, as shown in Figure7 (d). Characteristic impedance (Z_{comm}) is $Z_{comm}= Z_{even}/2$. Length of

the TL is assumed as the distance between the two ends of twisted-pair cable. A difficulty problem is to determine delay time of the TL or wave velocity along the TL. Strictly speaking, there exist different propagation modes with various velocities due to insulation coat around the TL. So the accurate solution of this parameter should be derived from the experimental data or full wave solver. In some cases [4] velocities of different propagation modes are viewed as the same, which can be approximately defined by:

$$v = v_0 \Big/ \sqrt{\varepsilon_r'} \quad \varepsilon_r' = \mathrm{C_{coat}}\Big/\mathrm{C_{no\_coat}} \qquad (10)$$

Where v_0 is velocity of light in vacuum, $\mathrm{C_{coat}}$ is capacitance of conductor with insulating, $\mathrm{C_{no\_coat}}$ is capacitance of pure conductor in vacuum. Note that above equation is based on the assumption that dielectric coating ($\varepsilon_r\varepsilon_0$) mixed with vacuum ($\varepsilon_0$) is considered as one equivalent uniform dielectric medium (ε' ε_0).
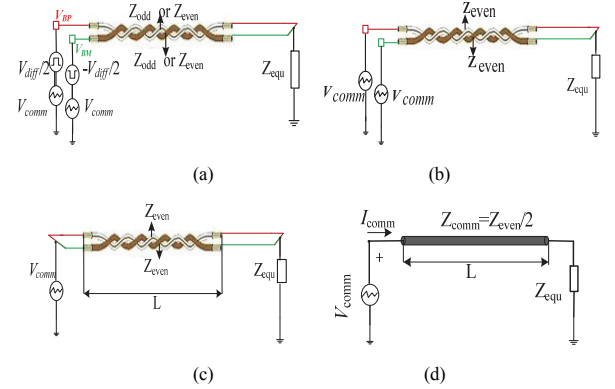

Figure 7. The procedure for simplifying the radiation model

B. The VHDL-AMS model for the common signal simulation

As described above for the fast methods, a common mode current as source to calculate radiated emissions is needed. Current along the point to point topology here was simulated using VHDL-AMS modelling language. Twisted-pair cable with ground as three-conductor MTL can be treated as a two-conductor TL for even mode signal, and a two-conductor TL for odd mode signal with different transmission characteristics. Each mode for the two-conductor TL can be solved based on simple TL theory [5]:

$$I_1(s) = Y_0(s)V_1(s) - (Y_0(s)V_2(s) - I_2(s))e^{-\gamma(s)l} \qquad (11)$$
$$I_2(s) = -Y_0(s)V_2(s) + (Y_0(s)V_1(s) + I_1(s))e^{-\gamma(s)l} \qquad (12)$$

Where $Y_0(s)$ is the characteristic admittance of frequency dependency, $\gamma(s)$ is the propagation constant and l is the length of TL. These equations cannot be directly applied in time domain solvers like VHDL-AMS. Therefore a transfer function technology using rational function approximation was implemented. The detailed description for MTL VHDL-AMS model is presented in [6], where a twisted-pair cable from Kromberg and Schubert (type "FLRYW") also used in this paper is presented and verified by experimental data. The VHDL-AMS models of other components in FlexRay networks are introduced and verified by experimental data in [7].

C. The influence of cable insulation to common mode propogation characteristic

Above TL model of VHDL-AMS has taken insulation into account. However the analytic radiation method is only implemented for TL without insulation, so it is necessary to consider and analyze the influence of insulation to common mode characteristics (impedance and velocity). Common mode propagation velocity v_{comm} can be evaluated approximately based on (10). Common mode impendence is defined by:

$$Z_{comm} = 0.5 \times Z_{even} \quad Z_{even} = \sqrt{\frac{L_{11} + L_{12}}{C_{11}}} \tag{13}$$

Here L_{11} is the loop self inductance of wire 1 to ground; L_{12} is the loop mutual inductance between wire 1 to ground and wire 2 to ground; C_{11} is the capacitance of wire 1 to ground, as shown in Figure 8. C_{12} is the capacitance of wire 1 to wire 2 that has no contribution to Z_{even} and v_{comm}, as shown in Figure 8.
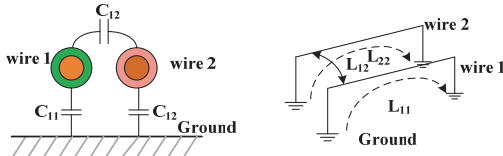

Figure 8. Coupling capacitance and inductance

FEM (Finite Element Method) was used to extract the L and C matrices. According to geometrical data, an elaborated model of a twisted-pair cable was constructed as shown in Figure 9. The parameters matrices are:

$$[L] = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} = \begin{bmatrix} 1.1812 & 0.9038 \\ 0.9038 & 1.1812 \end{bmatrix} uH/m \tag{14}$$

$$[C_{coat}] = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} 7.42 & 41.097 \\ 41.097 & 7.42 \end{bmatrix} pF/m \tag{15}$$

$$[C_{no\_coat}] = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} 7.01 & 21.708 \\ 21.708 & 7.01 \end{bmatrix} pF/m \tag{16}$$
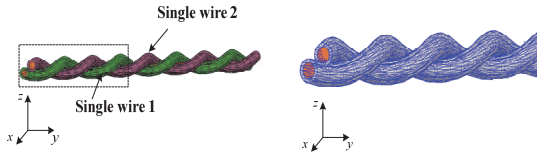

Figure 9. 3D model of twisted-pair cable (left) and its partial FEM mesh (right)

According to (10) and (13) the characteristic impedance and propagation velocities can be computed as shown in Table 1.

TABLE I.   THE COMMON MODE PARAMETERS INFLUENCED BY INSULATING COAT

	Cable of insulation	Cable of no insulation
Z_{comm}	265Ω	272.68Ω (+2.9%)
v_{comm}	0.97 v_0	v_0

From above results, the common mode impedance without insulation is 2.9% larger than that with insulating coat; and the propagation velocities are nearly the same between both cases. Therefore it is reasonable to simplify the virtual twisted-pair cable to a single TL without insulation. Note that the height of twisted-pair cable above ground plane is 50mm here. It should be problematic to employ analytic method when the cable is very close to ground or other parameters lead to great changes of common mode characteristics.

IV. SIMULATION OF THE RADIATED EMISSION

This paper only considers the common mode signal resulting from non-synchronized driver signals at BP and BM of transceiver (asymmetric delay time). How the differential mode to common mode conversion on TL can happen is not discussed here.

A. Radiation simulation for a point to point topology

The common mode currents of FlexRay point to point topology (as shown in Figure 1) were simulated using VHDL-AMS modeling language in *Systemvision* [8]. Radiation model setup is shown in Figure 10. For simplicity when using full wave methods, the receiving transceiver is not considered here.
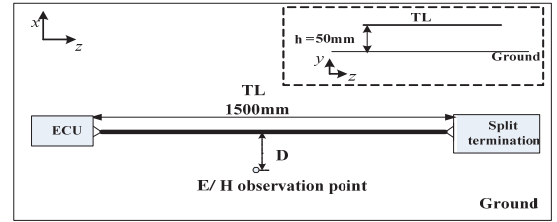

Figure 10. The setup for radiation simulation

The asymmetric delay time (BP to BM) is 5 ns; common model choke (CMC) is not taken into account here. Figure 11 shows differential mode voltages on BP and BM nodes of transceiver and common mode voltage V_{comm}. Figure12 shows differential mode currents through BP and BM of transceiver and common mode current I_{comm}. V_{comm} and I_{comm} are calculated using VHDL-AMS based on TL theory. In order to verify this TL model, V_{comm} as source was assumed in MoM equivalent model. In Figure 13, the common mode current calculated by TL theory and MoM match very well. For purpose of employing the analytic method to predict radiated fields from the equivalent TL (as shown in Figure 7(d)), common mode voltages and currents at the two ends of TL have to be calculated by VHDL-AMS. Differing from the analytic method, multiple-dipole method needs the current along the whole TL. Thereby the TL is subdivided into N short dipoles,
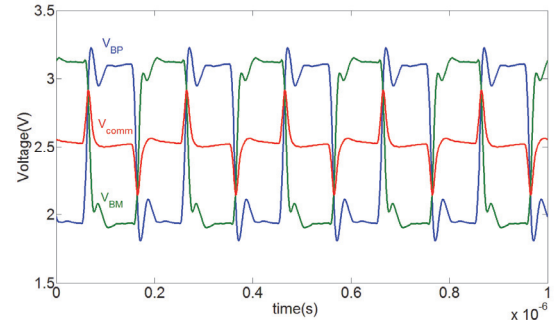

Figure 11. Differential voltages (V_{BP} and V_{BM}) and common voltage (V_{comm})

where N is determined by:

$$N=15 \times L/(t_r \times v_0) \qquad (17)$$

Here t_r is the rise time of the signal (10ns in this paper); v_0 is the velocity of light in vacuum; L is the length of TL. The current on each dipole is calculated with VHDL-AMS simulation.
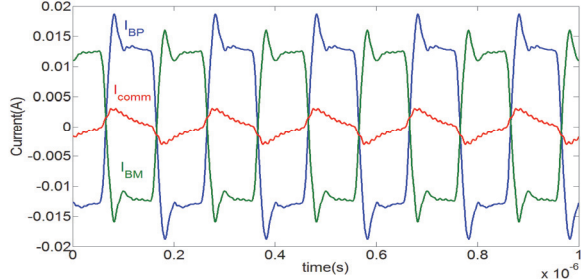

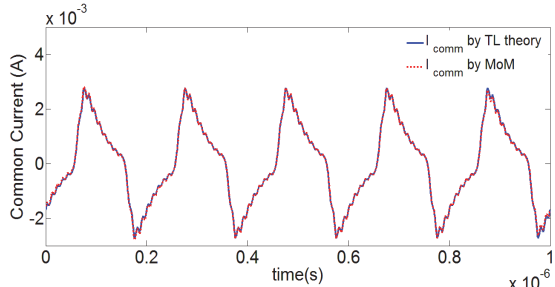Figure 12. Differential mode currents (I_{BP} and I_{BM}) and common mode current (I_{comm})

Figure 13. Common mode current calculated by TL theory and MoM

For faster computation times of full wave methods, fields observation point is set to D=60 mm. Figure 14 shows x-direction electric field in time domain, where the results from these four different methods (analytic method, multiple-dipole method, MoM and FIT) match very well. However efficiency of these four methods makes a big difference. Figure 16 shows the CPU time for different methods: Analytic method is fastest, FIT is the slowest method. Additionally we also compared the results in frequency domain using Fast Fourier Transform (FFT) from 1 MHz to 200 MHz. Main resonance frequency points of four methods match very well. Excepting FIT, the curves of other three methods nearly coincide above 4 MHz. Compared to the full wave methods, the analytic or multiple-dipole method obtains the equal accuracy at low cost of computation time when predicting radiated emissions from a cable parallel to ground.
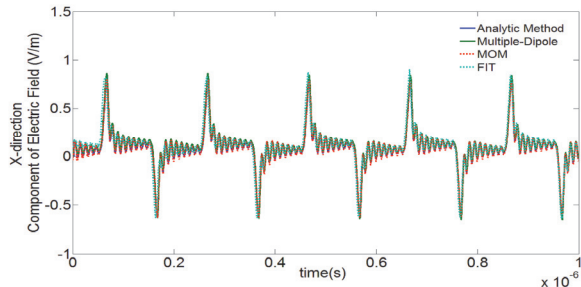

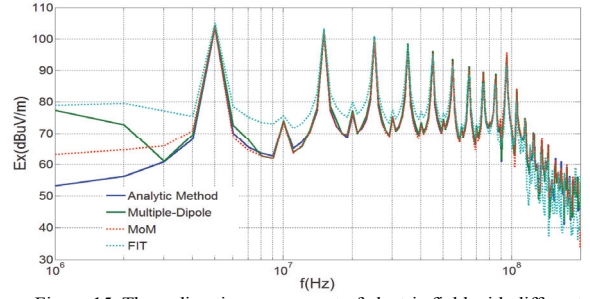Figure 14. The x-direction component of electric field with different methods in time domain

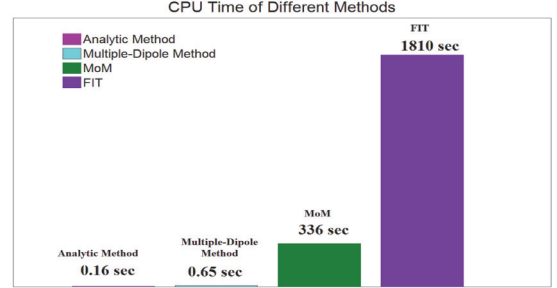Figure 15. The x-direction component of electric field with different methods in frequency domain

Figure 16. The CPU time of different methods for calculating radiation

B. Radiation simulation for a FlexRay point to point topology with common mode choke

In order to suppress such unexpected common mode emissions in a FlexRay network a common mode choke (CMC) is of often used. For common mode signal, CMC [9] exhibits great inductance and consequently great impedance at high frequencies. For radiation simulation a FlexRay point to point topology was investigated as shown in Figure 10. Here CMC of Epcos-B82789C0104H001 is used. VHDL-AMS models for common mode chokes are provided by the suppliers to some extent. The asymmetric delay time (BP to BM) is 5 ns; distance of field observation point to TL is D=1000 mm and receiving transceiver is also considered in this case. Figure 17 and Figure 18 depict x-direction electric field in time domain and frequency domain (1 MHz - 200 MHz) respectively. Common mode electromagnetic emissions are large when no CMC is applied to FlexRay network. It is obvious that the field emissions are suppressed to nearly zero after using CMC in time domain; field emissions decrease by more than 40 dB for frequencies above 10 MHz.
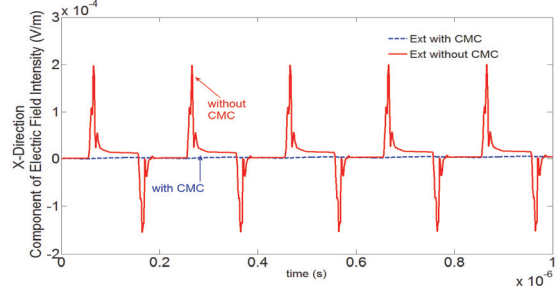

Figure 17. The x-direction component of electric field with CMC and without CMC in FlexRay point to point topology.
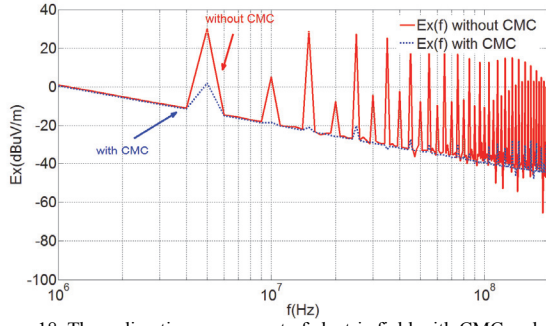
Figure 18. The x-direction component of electric field with CMC and without CMC in frequency domain.

C. Radiation simulation for a FlexRay passive network

The point to point topology is very simple. In this section we consider and calculate a more complex passive network. Figure 19 illustrates this topological structure which comprises four transceivers where ECU 1 is the sending transceiver and the others are receiving transceivers. This network is 50 mm above reference ground. Total length of bus cable in this simulation is 4000mm. Asymmetric delay time of sending transceiver is 5ns between BP and BM. CMC is not considered in this simulation. Field observation point is (x=150 mm, y=50 mm, z=L/2 mm). Split_Lowohmic and Split_Highohmic are termination types to improve EMC behavior [10].
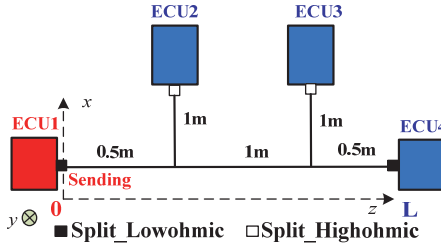

Figure 19. The setup of FlexRay passive topology

When combining common mode current obtained from VHDL-AMS circuit simulation, it is very simple and convenient to calculate radiated emissions from any FlexRay passive network by fast methods proposed here. Figure 20-21 show electric field in time and frequency domain respectively at observation point.
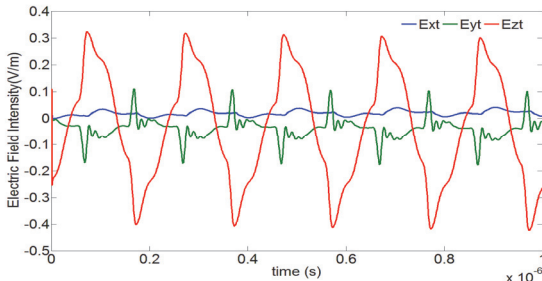

Figure 20. The x-, y- and z-direction component of electric field in time domain of the FlexRay passive topology
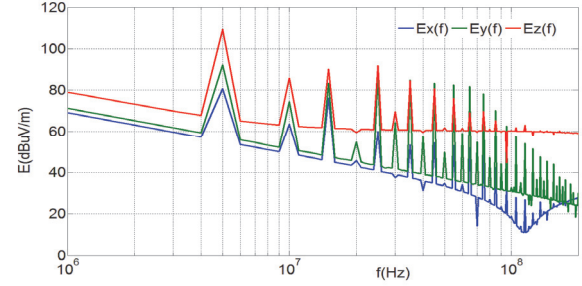

Figure 21. The x-, y- and z-direction component of electric filed in frequency domain of FlexRay passive topology

V. CONCLUSION

The presented fast methods, analytic and a multiple-dipole method, combined with VHDL-AMS, can be used to calculate radiated emissions from twisted-pair cables of FlexRay bus systems. Compared to full wave methods the fast methods are easier to handle due to its simplicity and higher efficiency. Accuracy for simple configuration is similar. Common mode currents were calculated based on TL theory implemented in VHDL-AMS modeling language. In order to construct an equivalent transmission line model for the common mode signal, a four-step procedure was proposed. Insulation around cables has no great influence on common mode characteristics. This was shown through FEM analysis. Therefore, the analytic method can be used for typical configurations of FlexRay bus systems. The radiated emissions of a point to point topology and linear a more complex passive topology were calculated using the fast methods and it was shown that CMC is an effective solution to suppress radiated emissions resulting from common mode signal. The presented method can be used to investigate influences of transceivers, termination, and cables on the field emissions in network analysis simulation environment. Bus systems can be optimized by this way without measurements or complex full wave field simulations.

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