Computationally-Effective Wideband Worst-Case Model of Transmission Line Radiation

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***Abstract*— The analytical model for radiation of a rectilinear uniform transmission line placed above a conducting screen is proposed. The model is intended for diagnostics (express analysis) of unintentional interference in large complexes of radio and electronic equipment. The model makes it possible to compute the envelopes of the amplitude-frequency characteristics for electric and magnetic fields in any spatial point above the screen. Single wire above ground plane, coaxial and triaxial lines with various grounding configurations are considered. The model is based on replacement of the complicated transmission line by an equivalent (in terms of the radiated field) single wire over ground plane. Correctness of the proposed model was verified by comparison with numerical simulation results in the frequency band from 10 kHz to 2 GHz for lines of length from 5 cm to 10 m with various load and source impedances, the line height above the ground plane was varied from the radius of the line to 5 m, the observation point position was up to 5 m away from the center of the line in arbitrary direction.**

Keywords—Electromagnetic radiative interference; transmission lines; cable shielding

I. INTRODUCTION

Estimation of interfering signals radiated by transmission lines is an important problem for electromagnetic compatibility (EMC) analysis [1]. Radiation models intended for express analysis of EMC in complicated systems (e.g., aircraft, ship) must meet the following specific requirements [2], [3]. 1) Results obtained by a model must not underestimate the field amplitude even if there are errors in initial data (the worst-case requirement). 2) A model must have high computational efficiency in order to provide practically acceptable time of analysis of complicated systems containing a lot of transmission lines. 3) In EMC analysis, it is often necessary to consider out-of-band interference [1]; therefore a model must be applicable in wide range of frequencies [4] (RE101 limit: Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz; RE102 limit: Radiated Emissions, Electric Field, 10 kHz to 18 GHz) and transmission-line load impedances. 4) In practice, the distance from radiating transmission line to observation point is usually in the range of 0.1 to 100 m, therefore (taking into account the mentioned frequency band of analysis) a model must be applicable both in far-field and in near-field zones.

Transmission line radiation models known to the authors have the following limitations. Calculation by methods of computational electromagnetics requires large computational expense. Simple analytical models [1] are applicable only in far-field zone. More complicated analytical models [5] are correct for any placement of the observation point, but they do not satisfy the worst-case requirement: amplitude-frequency characteristics (AFCs) of the fields are jagged in high frequency band due to resonances, and interference causes the jagged spatial distribution of the fields. At last, the model proposed in [6] satisfies the requirements given above, but it does not provide the complete solution to the problem (it does not point out a way for worst-case estimation of current waves' amplitudes) and it is correct only for single wire placed above the ground plane.

The objective of this paper is to develop such model of radiation from transmission lines of various configurations (single wire above ground plane, coaxial, triaxial) that satisfies the above-mentioned requirements.

The paper is organized as follows. The statement of the problem, its physical model and the approximations being used are described in Section II. Solution to a problem of estimating fields radiated by a single wire above ground plane is presented in Section III. Generalizations that account for shields and for various configurations of grounding are made in Section IV. Validation of the developed model is described in Section V.

II. PHYSICAL MODEL

In most of practically important cases, the radiating line is located inside metallic hull of on-board system (aircraft, ship, van, etc.). Let us define simplifications used to develop the model. Only the nearest (to the transmission line) conducting surface is considered, this surface is modeled as an infinite perfectly conducting plane. So, the impact of the hull on the radiated field is accounted by the method of images [7], [8].

Straight-line transmission lines parallel to the ground plane are considered. Currents in cross-section of the central conductor and shields of the line are assumed to be distributed symmetrically. It is supposed that the radiation power of the transmission line is many times less than the power transmitted through the line from the source to the load.

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Grounding of the transmission line central conductor or shield is described as follows. The central conductor or any shield terminal can be connected to the ground plane by a vertical wire (impedance of that wire is assumed to be zero). The radiation from the vertical wires is not accounted in our model, and it can be calculated by other models [3].

The following symbols are used for notation of grounding of the central conductor or the shield end: 1 – grounding exists, 0 – grounding does not exist. The first two positions in notation of the line grounding configuration correspond to the central conductor, the next two positions correspond to the inner shield, the last two positions correspond to the outer shield (so, four symbols are used for notation of a coaxial line grounding configuration). A symbol for grounding of the source side end is written first, and symbol for grounding of the load side end is written second. The following grounding configurations of a coaxial line are considered: the central conductor and the shield are grounded at the source, return current flows through the shield (1010); the central conductor and the shield are twice grounded, path of return current depends of frequency (1111); the central conductor is twice grounded, the shield is once grounded (1110 and 1101), return path is the ground plane. Eight configurations are considered for a triaxial line: the central conductor and shields are twice grounded (111111); the central conductor and the outer shield are twice grounded, the inner shield is grounded at the load (110111); the central conductor and the inner shield are twice grounded, the outer shield is grounded at the source (111110); return current flows through the inner shield, the outer shield is twice grounded (101011); return current flows through the inner shield, the outer shield is once grounded (101010). In addition, configurations 110101, 100110 and 101110 rarely used in practice are considered.

The axis of the transmission line is placed at height h above the ground plane; l is the length of the line. The observation point position is defined in right-hand rectangular coordinate system with origin at the ground plane under the line center. Axis *Ox* is directed along the transmission line from the source to the load, axis *Oz* is directed along normal to the ground plane (see Figure 1 in [6]).

Subject to above defined approximations, initial data for the actual problem are the grounding configuration, geometrical and physical characteristics of the line (Figure 1). In addition, currents in the central conductor are considered to be given (they are determined by a technique described in [9]): current I_S at the source (in the start of the line) and current I_L at the load (in the end of the line). It is required to develop a worst-case model of AFCs for electric and magnetic fields in the observation point.

III. Worst-Case Radiation Model of Single Wire Above Ground Plane

In case of uniform long transmission line (e.g. single wire above ground plane), equations of telegraphy have solution in the form of current and voltage waves propagating along the line. For harmonic dependence of voltage and current on time $U(t) = U_0 \exp(-j\omega t)$, $I(t) = I_0 \exp(-j\omega t)$ the solution can be

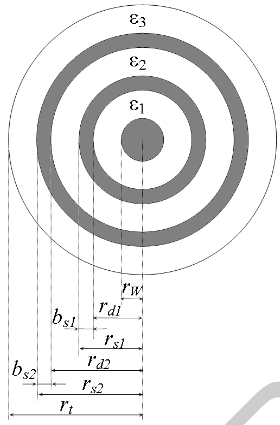

Fig. 1. Characteristics of transmission lines: r_W – radius of the central conductor, r_{d1} – radius of the central conductor and the dielectric coating (i.e., radius of the unshielded wire), r_{s1} – outer radius of the inner shield, r_{d2} – radius of the inner shield and the dielectric coating (i.e., radius of the coaxial cable), b_{s1} – inner shield thickness, r_{s2} – outer radius of the outer shield, b_{s2} – outer shield thickness, r_t – outer radius of triaxial cable; ε_3 – permittivity of the outer isolation, ε_2 – permittivity of isolation between the shields, ε_1 – permittivity of isolation between the central conductor and the inner shield.

represented in the form [1]:

$$\begin{cases} U(x) = Z_0 (A_1 \exp(\gamma x) - A_2 \exp(-\gamma x)) \\ I(x) = A_1 \exp(\gamma x) + A_2 \exp(-\gamma x), \end{cases} \quad (1)$$

where $j = \sqrt{-1}$, $\gamma \approx ik + \delta = i\omega\sqrt{L_{0T} C_{0T}} + 0.5 R_{0T} / Z_0$ is propagation constant for current and voltage waves in the line, $\omega = 2\pi f$ is cyclic frequency of harmonic oscillations, $Z_0 = \sqrt{L_T / C_T}$ is the line impedance, L_{0T} and L_T are per-unit and full inductance of the line, C_{0T} and C_T are per-unit and full capacitance of the line, R_{0T} is per-unit resistance of the line, A_1 and A_2 are complex amplitudes of current waves, defined by given values $I_S = I(-l/2)$, $I_L = I(l/2)$ of current at the line ends:

$$\begin{aligned} A_1 &= (I_L \exp(\gamma l / 2) - I_S \exp(-\gamma l / 2)) / (2i \sin((k - i\delta)l)), \\ A_2 &= (I_S \exp(\gamma l / 2) - I_L \exp(-\gamma l / 2)) / (2i \sin((k - i\delta)l)). \end{aligned} \quad (2)$$

Let us define two frequency bands for development of the worst-case model: a low-frequency band and a high-frequency band. It is empirically determined that the upper frequency bound of the low-frequency band can be defined by the following formula:

$$f_{tr} = \begin{cases} \left(2\pi\sqrt{0.5 L_T C_T}\right)^{-1}, & C_L \le C_T; \\ \left(2\pi\sqrt{0.15 L_T C_T}\right)^{-1}, & C_L > C_T, \end{cases} \quad (3)$$

where C_L is the load capacitance (Fig. 2).

In the low-frequency band the currents I_S and I_L are directly substituted in the system (2). In the high-frequency band, current waves' AFCs $|A_1(f)|$ and $|A_2(f)|$ computed by (2) are jagged as a result of resonances. This makes the solution unstable to errors in parameters values. Therefore, in this band amplitudes A_1 and A_2 are calculated from the modules of currents I_S and I_L:

$$A_{1,2}^{HF} = \begin{cases} M_{SL} I_{\max\, S,L}\,, & f \in [\,f_{ln} - \Delta f\,,\, f_{ln} + \Delta f\,]; \\ M_{SL} \left| I_{S,L} \right|, & f \notin [\,f_{ln} - \Delta f,\, f_{ln} + \Delta f\,], \end{cases} \quad (4)$$
$$\Delta f = \delta_f\, f_{ln}, \quad f_{ln} = cn/2l, \quad n = 1, 2, ...,$$

where f_{ln} are frequencies of resonances, δ_f is a relative error of the resonance frequency f_{ln} definition, c is the velocity of light, M_{SL} is a coefficient accounting for multiple reflections of current waves from the source and the load, $I_{\max S,L}$ is a maximum of the current (with account for ohmic losses):

$$I_{\max\, S,L} = \left| I_{S,L} \right| Z_0 / R_T\,, \quad (5)$$

R_T is the total ohmic resistance of the line (with account for skin effect).

Expression for M_{SL} is as follows:

$$M_{SL} = 1 + \Gamma_S \Gamma_L / (1 - \Gamma_S \Gamma_L), \quad (6)$$
$$\Gamma_S = |Z_S - Z_0| / |Z_S + Z_0|, \quad \Gamma_L = |Z_L - Z_0| / |Z_L + Z_0|,$$

where Z_S is the source impedance, Z_L is the load impedance, Γ_S and Γ_L are modules of reflection coefficients from the source and from the load (it is necessary to fulfill the condition $\Gamma_S \Gamma_L < 1$).

It is empirically determined that calculation of current waves' amplitudes by (4) together with the use of worst-case model [6] allows to obtain the field AFC envelope in the high-frequency band.

As a result of transition from expression (2) to (4), discontinuities can appear in AFCs of the current waves at the frequency f_{tr} (3). To eliminate it, in the low-frequency band quantities A_1 and A_2 computed by expression (2) are multiplied by the smoothing coefficient

$$T_{1,2} = 1 + K_{1,2} \exp(-\,(f - f_{tr})^2 / (0.5\, f_{tr})^2)), \quad (7)$$
$$K_{1,2} = M_{SL}\, |\, I_{S,L}(f_{tr})\,| / A_{1,2}(f_{tr}) - 1.$$

As a result, amplitudes A_1 and A_2 of the current waves are computed on basis of I_S, I_L in the following way:

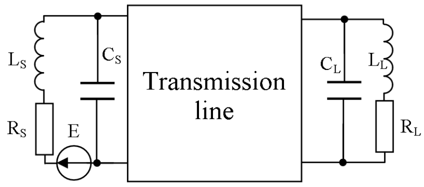

Fig. 2. Circuit of the transmission line connection. Parameters of the source: E is emf, R_S is ohmic resistance, L_S is inductance, C_S is capacitance. The load parameters: R_L is ohmic resistance, L_L is inductance, C_L is capacitance.

$$A_{1,2}^{total} = \begin{cases} T_{1,2} \cdot A_{1,2}\,, & f \le f_{tr}\,; \\ A_{1,2}^{HF}\,, & f > f_{tr}\,. \end{cases} \quad (8)$$

Required AFCs of the fields are found by substitution of complex amplitudes (8) in the worst-case model of radiation of the single wire above ground plane [6].

IV. Worst-Case Radiation Model of Shielded Transmission Lines

The model is based on the following principle: a complex transmission line is replaced by an equivalent single wire (above ground plane) which radiates the same field. For that, currents flowing through the ground plane under the transmission line are substituted for I_S and I_L in the developed worst-case model of the single wire above ground plane (see Section III). Let us denote these currents as current I_{SG} at the line end near the source and current I_{LG} at the line end near the load. Amplitudes of currents I_{SG} and I_{LG} are determined as a product of the current flowing through the central conductor and correcting coefficients which take into account type of the line and grounding configuration of the shields. These coefficients were derived by generalization of low-frequency coefficients of inductive and capacitive coupling [1], [3] to the case of high frequencies by accounting for skin effect.

A. Shield Characteristics Determined by Skin Effect

Change of resistance determined by skin-effect is sufficient at high frequencies.

Resistance of a shield in the form of cylindrical tube with outer radius r_S and small thickness b_S is defined by the formula obtained by integration of current density over the cross-section area:

$$R_{Sh} = l / (2\pi\sigma\delta(r_s - \delta + (b_s + \delta - r_s)\exp(-b_s / \delta))))\,, \quad (9)$$

where $\delta = (\pi\mu_0\sigma f)^{-0.5}$ is the skin-layer thickness [7], σ is the shield material conductivity.

For braided shield, radiating power is increased with increasing frequency as result of diffraction through apertures in the shield. In framework of the model this effect is taken into account by the empirical coefficient:

$$K_b = 1 + p_1(1 - \exp(-b_s/(p_2\delta)^2)) , \tag{10}$$

where p_1 is the shielding parameter equal to 0.02 [10], p_2 is the ratio of the braid thickness to the characteristic size of aperture in the braid (chosen equal to 10).

If the shield is made from foil then the attenuation produced by the shield is increased with increasing of frequency as result of skin-effect, and the empirical coefficient for shielding is written in form:

$$K_f = 1 - p_1 \exp(-b_s/\delta) . \tag{11}$$

B. Single-Shielded Wire (Coaxial Cable)

1) For the grounding configuration 1010, the return current flows through the shield. The current flowing through the ground plane is determined by capacitive coupling between the shield and the ground plane. Multiplier characterizing the capacitive coupling is calculated by the formula:

$$S_{C1} = j\omega R_{Sh1} C_{Sh1} / (1 + j\omega R_{Sh1} C_{Sh1}) , \tag{12}$$

where R_{Sh1} is computed by (9), and the capacitance of cylindrical shield over the ground plane is determined by

$$\begin{aligned} C_{Sh1} &= 2\pi\varepsilon_{eff1}\varepsilon_0\, l / \ln(2h/r_{s1}), \\ \varepsilon_{eff1} &= \frac{\varepsilon_2 \ln(2h/r_{s1})}{(\ln(r_{d2}/r_{s1}) + \varepsilon_2 \ln(2h/r_{d2}))}, \end{aligned} \tag{13}$$

where ε_{eff1} is effective dielectric permittivity obtained under condition $r_{d2} < 4h$.

For computation of fields' strength, the average amplitude of current I_W in central conductor of the coaxial line is obtained:

$$I_W = 0.5 \cdot (|I_S| + |I_L|) . \tag{14}$$

Value of I_W is multiplied by (10) or (11), depending on the shield type.

Thus, currents flowing through the ground plane are

$$\begin{aligned} I_{SG} &= K_{b,f} \cdot S_{C1} \cdot I_W , \\ I_{LG} &= 0. \end{aligned} \tag{15}$$

2) For multiple-grounded shield (the configuration is 1111) there is an inductive coupling between them and the ground plane. The current flowing through the ground plane is determined by the multiplier:

$$S_{L1} = 1 - j\omega / (j\omega + R_{Sh1}/L_{Sh1}) , \tag{16}$$

where L_{Sh1} is inductance of the shield placed over the ground plane:

$$L_{Sh1} = (2\pi)^{-1}\mu_0 l \; \ln[2h/r_{s1} - 1]. \tag{17}$$

To provide the worst-case estimation of current I_{SG} in case of inductive coupling, at $f > f_{tr}$ the frequency f_{tr} (3) is substituted in (16). Then one can write in analogue with (15):

$$\begin{aligned} I_{SG} &= \begin{cases} K_{b,f} \cdot S_{L1}(f) \cdot I_W , & f \le f_{tr} ; \\ K_{b,f} \cdot S_{L1}(f_{tr}) \cdot I_W , & f > f_{tr} , \end{cases} \\ I_{LG} &= I_{SG} \exp(-jkl\xi), \quad \xi = 0.5. \end{aligned} \tag{18}$$

It is empirically determined that the value $\xi = 0.5$ provides a worst-case behavior of the field model in the low-frequency band.

3) For lines with grounding configurations 1110 and 1101, the current flowing through the ground plane is equal to the current in the central conductor $(I_{LG} = I_L, I_{SG} = I_S)$, therefore the radiation of such lines is modeled by technique intended for single wire above ground plane (see Part III). However, additional resonances are appeared for these lines types at frequencies determined by capacitance C_{T1} of the central conductor in the shield and inductance L_T of the central conductor over the ground plane. Therefore, transition from the low-frequency band to the high frequency band must be performed at the frequency f_{tr1} smaller than f_{tr} (3):

$$\begin{aligned} f_{tr1} &= \min\left\{0.8\left(2\pi\sqrt{0.5 L_T C_T}\right)^{-1}, \left(2\pi\sqrt{0.5 L_T C_{T1}}\right)^{-1}\right\}, \\ C_{T1} &= 2\pi\varepsilon_1\varepsilon_0 l / \ln(r_W/r_{d1}). \end{aligned} \tag{19}$$

C. Triaxial Cable

Model of a triaxial cable radiation is based on association of each grounding configuration with combination of multipliers describing capacitive and inductive couplings of the central conductor, shields and the ground plane.

Let us introduce multiplier S_{C12} characterizing the capacitive coupling of two shields by analogy with (12):

$$\begin{aligned} S_{C12} &= j\omega R_{Sh1} C_{Sh12} / (1 + j\omega R_{Sh1} C_{Sh12}), \\ C_{Sh12} &= 2\pi\varepsilon_2\varepsilon_0 l / \ln(r_{d2}/r_{s1}), \end{aligned} \tag{20}$$

where R_{Sh1} is resistance of the inner shield, C_{Sh12} is capacity between the inner and the outer shield.

One can write for inductive coupling of shields similar to (16):

$$S_{L12} = 1 - j\omega / (j\omega + R_{Sh1} / L_{Sh12}) , \\ L_{Sh12} = (2\pi)^{-1} \mu_0 l \ln\left[r_{s2} / r_{s1} \right], \tag{21}$$

where L_{Sh12} is inductance of the inner shield placed coaxially inside the outer shield (it is determined in the assumption that going-down current flows through the inner shield and return current flows through the outer shield).

Currents through the grounding plane are computed by formulas analogous to (15) and (18). Parameters used for their computation are given in Table I. S_{C2} and S_{L2} are multipliers analogous S_{C1} to S_{L1}, they are computed by (12) and (16) with the use of the outer shield parameters.

V. Model Validation

Validation was performed by comparison of fields calculated by the developed model with reference fields obtained numerically.

Model of a single wire above ground plane was validated for the following values of parameters (see Fig. 1): r_W is 0.18, 0.50, 0.56 mm; r_{d1} is 0.50, 1.25, 1.50 mm; ε_1 is 1, 2.3, 3; h is 2, 3, 10, 40 mm; l is 0.05, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0 m.

Coaxial transmission line model was validated for various grounding configurations and the following line characteristics: r_W is 0.24, 0.47 mm; r_{d1} is 0.74, 1.48 mm; ε_1 is 1, 2, 3; b_{s1} is 0.26, 0.52 mm; the screen type: foil, braid; ε_2 is 3; thickness of the outer dielectric is 0.5, 0.7 mm; h is 10, 20, 50, 100 mm; l is 0.25, 0.50, 1.0, 2.0, 5.0 m.

Model of a triaxial transmission line was obtained by addition of the outer shield (b_{s2} is 0.33, 0.5 mm) and the dielectric coating around the shield (ε_3 is 2.3, 3; thickness is 0.5 mm) to a coaxial transmission line. Validation was performed for eight practically important grounding configurations (see Table 1).

The following load and source parameters (see Fig. 2) are used for all types of transmission lines: R_L is 5, 50, 500 Ohm; L_L is 10^{-50}, 10^{-9}, 10^{-6}, 10^{-3} H, C_L is 10^{-50}, 10^{-12}, 10^{-9}, 10^{-6} F; R_S is 0, 5, 50 Ohm; L_S is 10^{-50}, 10^{-9}, 10^{-6} H, C_S is 10^{-50}, 10^{-12}, 10^{-9} F.

Distance from the origin (see Section II) to the observation points was varied from 1 cm to 5 m in diverse directions. The maximal modeling frequency $f_{\max} = 0.1c / \Delta$, where Δ is maximal size of the line cross-section with a glance of the ground plane (e.g. $S = h + r_t$ for a triaxial transmission line).

The validation results example for the worst-case radiation model of a triaxial transmission line placed above the grounding plane in case of the grounding configuration 111111 is shown in Fig. 3.

TABLE I. Summary Information about Computation of Field Radiated by Triaxial Cable

Grounding configuration	***Primary path of return current***	***Formula for f_{tr}***	***Correcting multiplier[a]***	***Expression for I_{LG}***
11 11 11	Shield 1	(3)	$S_{L12}S_{L2}$	$I_{LG} = I_{SG}e^{-jkl\xi}$
11 01 11	Shield 2	(3)	S_{L2}	$I_{LG} = I_{SG}e^{-jkl\xi}$
10 10 11	Shield 1	(3)	$S_{C12}S_{L2}$	$I_{LG} = 0$
11 11 10	Shield 1	(3)	S_{L1}	$I_{LG} = I_{SG}e^{-jkl\xi}$
10 11 10	Shield 2	(19)	$2S_{C2} / S_{C12}$	$I_{LG} = 0$
11 01 01	Ground plane	(19)	1	$I_{LG} = I_{SG}e^{-jkl\xi}$
10 10 10	Shield 1	(3)	$2S_{C12}S_{C2}$	$I_{LG} = 0$
10 01 10	Shield 2	(19)	$2S_{C2}$	$I_{LG} = 0$

a. To obtain current I_{SG} from current I_W

The red line corresponds to numerical modeling results of fields radiated by the complete system including the transmission line and vertical grounding wires (the source and the load are presented by lumped elements). The modeling was performed by the following algorithm: 1) to compute the ground-plane current distribution along the line by the MTL method, 2) to consider an equivalent infinitely thin wire with retrieved current distribution placed along the cable axis (currents at grounding wires for equivalent wire are considered equal to currents I_{SG} and I_{LG} at ends of the line), 3) to compute field distribution of the equivalent wire by FDTD method. The ground plane was modeled by a metallic plate with sizes $6l$ x $6l$ m.

The blue line was obtained as follows. Amplitudes of the current waves are determined with help of (2) by numerically computed currents I_{SG} and I_{LG}. Obtained amplitudes of the current waves are substituted into the truncated model of a wire radiation [6]. Besides, the radiation of vertical grounding wires is taken into account by the technique given in [6]. Let us define the field computation by the truncated model on the basis of numerically computed currents as a combined model.

The green line was computed analogously to the blue one but without accounting for radiation of the grounding wires. Good agreement between the red and the blue lines demonstrates that field computation above the finite (big) ground plane with help of FDTD method can be replaced by calculation according to the truncated model [6]. This makes it possible to use the field calculated by the combined model without accounting for the grounding wires (ref. the green line) as the etalon, because fields radiated by these wires are ignored intentionally in the developed model (see Section II).

The black line corresponds to the developed worst-case model.

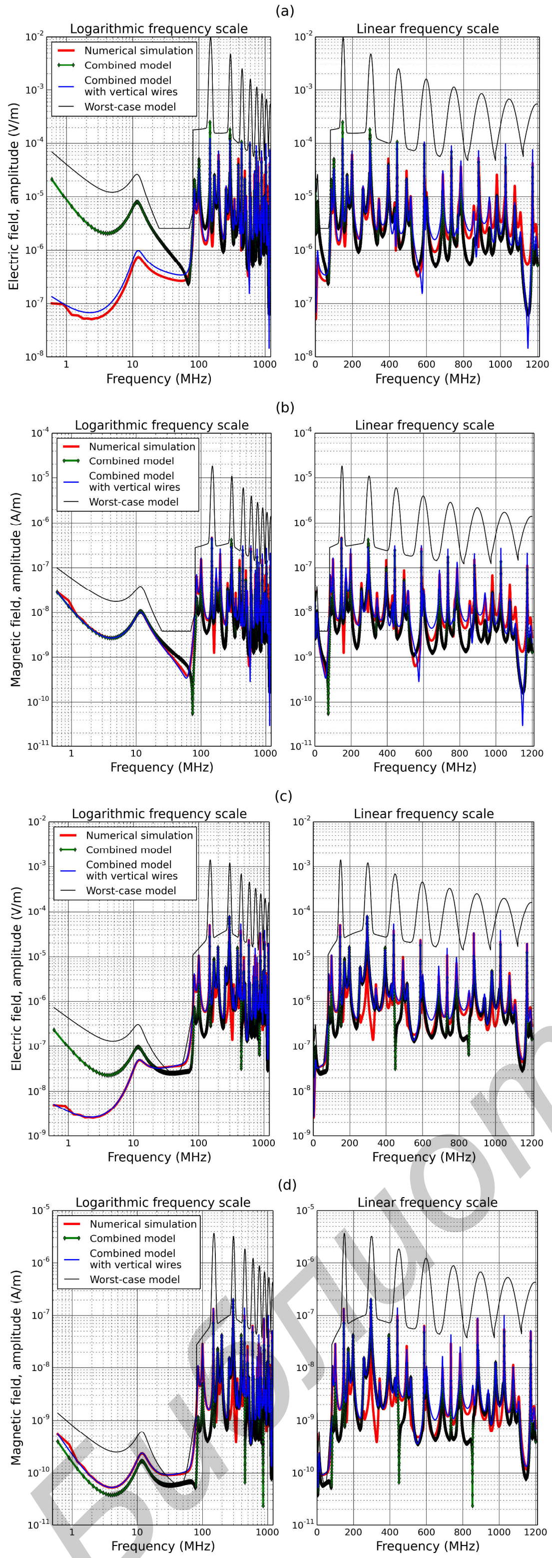

Fig. 3. Validation results for the radiation model of triaxial cable. Simulation parameters: l=1 m, h=20 mm, r_w=0.47 mm, r_{d1}=1.475 mm, r_{S1}=1.8 mm, r_{d2}=2.3 mm, b_{S1}=0.325 mm, r_{S2}=2.8 mm, b_{S2}=0.5 mm, r_t =3.3 mm; ε_1=2.3, ε_2=3.0, ε_3=2.3, E=1 V, R_S=5 Ohm, L_S=1 nH, C_S=1 nF, R_L=50 Ohm, L_L=1 µH, C_L=1 nF, copper conducors are used.
a) b) AFCs of electric and magnetic fields at observation point (-1,0,0.04) m;
c) d) AFCs of electric and magnetic fields at observation point (-2,2,2) m.

Results of the validation show that the developed worst-case model satisfies the requirements stated in Section I. High computational efficiency of the model is provided by using appropriate techniques for computation of currents [9] and fields [6], and also by using analytical expressions (1)-(21). For triaxial cable and grounding configuration 111111, the average time needed for computation of one point of AFC is 144 µs in case of processor AMD FX(tm)-4100 Quad-Core and memory type DDR3-1333.

VI. Conclusion

The developed worst-case model of transmission line radiation can be used for diagnostics (express-analysis) of EMC between on-board radio-electronic equipment of big systems: cars, aircrafts, ships, etc. [3]. Frequency range of the proposed model (10 kHz to 2 GHz) is restricted by capabilities of numerical methods used for its validation (see Section V).

The loss of information about phase of the current waves is a drawback of the model. This may cause the electric field overestimation by an order of magnitude in the low-frequency band. Mentioned drawback appears only for shielded transmission lines with multiple grounding of shields.

Possible directions of the model improvement are as follows: accounting for the influence of such objects (usually located near to the transmission line) that can not be modeled by the ground plane; accounting for natural resonances of on-board system hull (based on its characteristic dimensions and equivalent Q-factor).

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