Wideband computationally-effective worst-case model of twisted pair radiation

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A computationally-effective model for radiation of a rectilinear twisted pair 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 and makes it possible to compute the worst-case amplitude-frequency characteristics for electric and magnetic fields. The model was validated by comparison with numerical simulation results in the frequency band from 10 MHz to 1.2 GHz (for balanced feed and load) and from 300 kHz to 1.2 GHz (for unbalanced terminations), the observation point was located above the screen from 4 cm to 2 m away from the center of the twisted pair in arbitrary direction.

1 Introduction

Estimation of interfering signals radiated by transmission lines (including twisted pairs) is an important problem for electromagnetic compatibility (EMC) analysis [1]. Radiated emission 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), as well as in wide range of transmission-line source and 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 frequency band mentioned in item 3) a model must be applicable both in far-field and in near-field zones.

Twisted pair radiation models known to the authors have the following limitations. Computation of the fields by numerical methods, e.g., by the method of moments [5], does not provide the required computational efficiency (ref. item 2 above). Radiation model [6] is computationally-efficient, but it can be used for calculation of the field only at small (compared to twist length) distances from the twisted pair axis. In [7], it is proposed to consider the twisted pair as a structure consisting of two helical antennas, but such approach does not permit to compute the field in the near-field region. Another model proposed in [7] is based on summation of the field radiated by each twist; this model is valid in both near- and far-field regions. However, all known models of twisted pair radiation are not worst-case, since no arrangements have been made by their authors in order to provide the stability of the field computation results to errors in initial data.

The objective of this paper is to develop such model of twisted pair radiation (for the cases of balanced and unbalanced terminations) that satisfies the above-mentioned requirements.

The developed model is based on replacement of the twisted pair by an equivalent (in terms of the radiated field) single wire, and the twisted pair radiation peculiarities (associated with existence of common-mode and differential-mode components of the current) are taken into account by introducing the correction factors.

2 Simplifications and approximations

Let us define simplifications used to develop the model. In most of practically important cases, the radiating twisted pair is located inside metallic hull of on-board system (aircraft, ship, van, etc.). Only the nearest (to the twisted pair) conducting surface is considered for the developed model simplification, this surface is modeled as an infinite metallic

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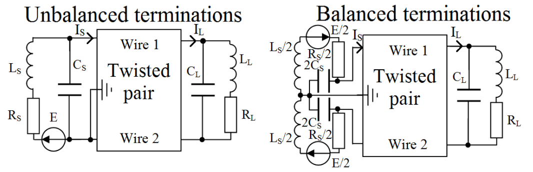


Figure 1: Circuits with balanced and unbalanced terminations of the twisted pair. Source parameters: E is emf, R_S is ohmic resistance, L_S is inductance, C_S is capacitance. Load parameters: R_L is ohmic resistance, L_L is inductance, C_L is capacitance.

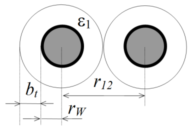


Figure 2: Twisted pair characteristics: r_W is wire radius, ε_1 is dielectric permittivity of isolation around the wires, r_{12} is distance between centers of the wires, b_t is thickness of the wire isolation.

perfectly conducting plane. The surface is considered as ground plane. Its impact on the radiated field is accounted by the method of images [8].

Straight-line twisted pairs parallel to the ground plane are considered. Currents in cross-section of the twisted pair are assumed to be distributed symmetrically. It is supposed that the radiation power of the twisted pair is many times less than the power transmitted through the line from the source to the load. Grounding of the twisted pair is described as connection of the twisted pair with the ground plane by a vertical wire (impedance of that wire is assumed to be zero). Balanced and unbalanced terminations of the twisted pair (Figure 1) are considered in this model. The radiation from the vertical wires is not accounted in our model, and it can be calculated by other models [3].

The axis of the twisted pair 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 [9]. Subject to above defined approximations, initial data for the actual problem are type of the twisted pair terminations (balanced or unbalanced), characteristics of the source and the load (Figure 1), geometrical and physical characteristics of the twisted pair (Figure 2). In addition, currents in one of twisted pair wires are considered to be given: 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 the electric and magnetic fields in the observation point placed above the ground plane.

3 Worst-Case Model of Twisted Pair Radiation

3.1 *Principle of Field Computation*

Currents in wires of the twisted pair can be presented as superposition of differential-mode component and common-mode component [1]. Consideration of these components is convenient in this case because properties of common-mode component emissions are significantly differ from properties of differential-mode.

Calculation of the electromagnetic field radiated by the twisted pair is carried out by the following algorithm: 1) amplitudes of currents I_S and I_L in one wire of the twisted pair are computed in according to the method stated in [10]; 2) current waves' amplitudes are determined by amplitudes of the currents in according to [11]; 3) the electric and magnetic fields of the single wire are computed by the current waves' amplitudes [9]; 4) Amplitudes of the fields calculated for the single wire are multiplied by correcting factors C and D in order to account for the twisted pair radiation peculiarities:

$$\begin{gathered} F_{2,a} = F_1(I_S, I_L) \cdot (C_{c,a} D_c + C_{d,a} D_d), \\ a \in \{b, n\}, F \in \{E, H\}, \end{gathered} \tag{1}$$

where F_2 is estimation of amplitude of the electric (E) or magnetic (H) field created by the twisted pair, a is parameter determining the type of twisted pair terminations (b is balanced terminations, n is unbalanced terminations), F_1 is estimation of amplitude of the electric or magnetic field created by single wire (computed by models [11] and [9]); $C_{c,b}$ ($C_{d,b}$) is ratio of common-mode (differential-mode) current component amplitude to amplitude of current in one of the twisted pair wires for balanced terminations, $C_{c,n}$ ($C_{d,n}$) is the same but for unbalanced terminations; D_c (D_d) is ratio of amplitude of the electric or magnetic field created by common-mode (differential-mode) current component to amplitude of the electric or magnetic field created by single wire (in the case of equal currents amplitudes).

The worst-case model enables to compute majorizing AFC $F_2(f)$ of the field radiated by the twisted pair, in the observation point. Majorizing AFC is not lower than maximums of the etalon AFC (derived numerically). This is support stability of the developed model to errors in parameters definition.

3.2 Common-Mode Current Radiation

Since currents of common-mode component in two wires are equal by value and phase, then value of the correcting factor $D_c = 2$.

3.3 Differential-Mode Current Radiation

When analyzing radiation of differential-mode current component, it is assumed that integer number of twists in twisted pair leads to maximal mutual compensation of the fields from each wire of the twisted pair. If number of twists is not integer, then radiation level of the twisted pair differential-mode current component sufficiently grows [1]. Therefore it is assumed for development of the worst-case model that twisted pair has half of twist uncompensated by radiation.

Position of twist half uncompensated by radiation is dependent on start point of compensated twists counting. Therefore empirical correcting factor is introduced in such a way that radiation level from all parts of the twisted pair will be decreased in equal degree:

$$\begin{gathered} D_d = G(f_{norm}) + \frac{2}{n}(1 - G(f_{norm})) + S_c, \\ f_{norm}(f_s, f_e, f) = \min(\max(\frac{f-f_s}{f_e-f_s}, 0), 1), \\ f_s = c/(2l), \qquad f_e = cn/(2l), \\ G(f) = -2f^3 + 3f^2, \end{gathered} \tag{2}$$

where $G(f)$ is weight function (monotonically increasing in the range (0,1) and having zero derivative at borders of the given range), n is number of twists in the twisted pair, c is the velocity of light in free space, S_C is amendment determined by capacitive coupling of wires in two-wire line:

$$\begin{gathered} S_C = 2j\omega R_W C_W/(1 + j\omega R_W C_W), \\ R_W = l/(2\pi\sigma\delta(r_W - \delta(1 - \exp(-r_W/\delta)))), \\ C_W = \pi\varepsilon_{eff}\varepsilon_0 l/\ln(r_{12}/r_W), \\ \omega = 2\pi f, \;\; \delta = (\pi\mu_0\sigma f)^{-0.5}, \\ \varepsilon_{eff} = 1 + 2(\varepsilon_1 - 1)\left(\frac{(r_W+b_t)^2 - r_W^2}{(r_{1,2}+r_W+b_t)^2}\right) \end{gathered} \tag{3}$$

where δ is the skin-layer thickness [8], σ is the wire material conductivity, C_W is capacity between wires [1], ε_0 is permittivity of a vacuum, μ_0 is permeability of a vacuum, ε_{eff} is effective dielectric permittivity [2].

It is empirically established that $S_C/D_d \le 0.1$, i.e. the main role in differential-mode component radiation is belong to geometric characteristics of the twisted pair cross-section and to uncompensated parts of twists.

3.4 Twisted Pair Radiation in Case of Balanced Terminations

Balanced terminations are used to decrease level of common-mode current component in the twisted pair. In this case amplitude I_d of differential-mode current component is many times more than amplitude I_c of common-mode component. Therefore, we can assume

$$C_{d,b} \approx 1, \;\; C_{c,b} = I_c/(I_d + I_c) \approx I_c/I_d, \tag{4}$$

then expression (1) will have the form

$$F_{2,b} = F_1(I_S, I_L)\cdot(2I_c/I_d + D_d), \;\;\; F \in \{E, H\}. \tag{5}$$

It is impossible to obtain ideal balance (zero common-mode current component) in real circuits. The following factors appearing due to technological errors, for example, lead to common-mode currents [12]: misphasing of the signal source, nonideal balancing transformers, incomplete symmetry of matching circuits of parasitic common-mode signal component. For example, value I_c/I_d can be 1/1000 for Ethernet 100BASE-TX [12]. Frequency characteristic I_c/I_d is given in detailed specifications of equipment; in the case it is not specified, then in working frequency band it can be estimated if we assume that time delay of signal at one source out against another out is equal to 10 % of signal rising time [12].

3.5 Twisted Pair Radiation in Case of Unbalanced Terminations

Common-mode current component has significant value in case of unbalanced terminations, and radiation level created by common-mode component is many times more than radiation level created by differential-mode component [1]. Therefore we can assume $C_{d,b} = 0$. Then

$$F_{2,n} = 2F_1(I_S, I_L) \cdot C_{c,n}, \quad F \in E, H, \tag{6}$$

where $C_{c,n}$ is empirically determined:

$$C_{c,n} = (\min(f, f_{tr})/f_{tr})^2, \tag{7}$$

$$f_{tr} = 1/(2\pi\sqrt{0.5 L_W C_W}). \tag{8}$$

L_W is mutual inductance between wires of the twisted pair [1].

4 Validation of Developed Model

4.1 Computation of Etalon Field Values in Case of Balanced Terminations

Validation was made by comparing fields computed by the developed worst-case model with etalon fields computed numerically.

Numerical computation of the field radiated by differential-mode current component requires accounting for geometric characteristics of twisted pair cross-section, which causes the need to use the mesh with small spatial step. In accordance to the Courant condition [13], it is necessary to use small time step in this case. In the total, computational expenses of etalons calculation for the twisted pair by general-purpose full wave computational electomagnetics methods are many times more than expenses of analogous calculation for single wire (for thin-wire approximation).

To decrease computational expenses, we compute etalon results in the following way: 1) each twist is divided in four parts having equal lengths; 2) each of four parts is replaced by a segment of straight-wire pair with the same length; 3) plane of the straight-wire pair segment is rotated on 90 degrees at transition between adjacent segments (Figure 3); 4) electromagnetic field of each wire ingressed in the straight-wire pair segment is computed by model of radiation from current wave in wire [9], currents in segments are computed by the method of multiconductor transmission lines (MTL); 5) calculated fields from wires of all segments are summed.

Example of the twisted pair AFCs computed by FDTD and approximate (see Figure 3) method is shown at Figure 4. As a result of inexact predicting of extremums by approximate method, these AFCs can sighnificantly differ at high frequencies.

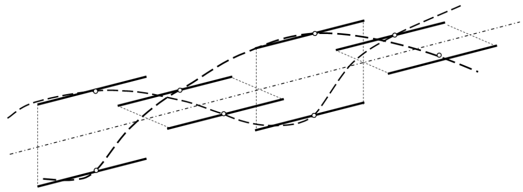


Figure 3: Model for one twist of the twisted pair in the form of four straight-wire-pair segments.

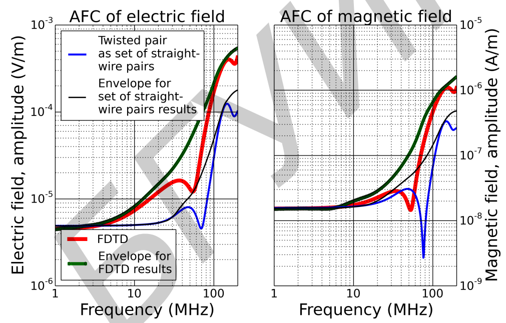


Figure 4: Comparison of the fields computed by FDTD method and by decomposition of twisted pair into segments of straight-wire pair. Parameters of the problem: observation point (0.25 m; 0; 2 m), E=1 V, l=1 m, h=0.02 m, $r_{1,2}$=2.5 mm, r_w=0.56 mm, ε_1=2.3, R_S=0, L_S=0, C_S=0, R_L= 50 Ohm, L_L=0, C_L=0, n=50.

But envelopes of these AFCs, which are important for validation of the development model, differ not so significantly (see Figure 4). In addition, possible underestimation of AFC envelope committed at computation of etalon field values by approximate method (see Figure 4) is compensated by excessive pessimism of the developed model (see Figure 5).

4.2 Computation of Etalon Field Values in Case of Unbalanced Terminations

Computation of etalon values of electric and magnetic field amplitudes for the twisted pair in case of unbalanced terminations is performed in two stages.

Stage 1. The fields radiated by the full system (including twisted pair and vertical grounding wires; the source and the load are represented by lumped elements) are estimated numerically by the following algorithm: 1) compute current distribution at ground plane along the twisted pair by the MTL method; 2) pass to consideration of equivalent infinitely thin wire placed along axis of the twisted pair (current distribution along the wire corresponds to current distribution from item 1); 3) compute electromagnetic field distribution from the equivalent wire by FDTD method (infinite ground plane is modeled by metallic plate with sizes 6x6 m).

Stage 2. Current waves' amplitudes are determined by current (calculated by MTL method) through the vertical grounding wire at the source [11]. Derived amplitudes of current waves are substituted in truncated model of the wire radiation [9]. Radiation of the vertical grounding wire is accounted by the method [9].

Stage 3. Amplitudes of the electric and magnetic fields are computed by analogy with stage 2 but without accounting for the grounding wire radiation (Fields from this wire are specially ignored in developed model, see Section 2).

Good agreement of values derived at stages 1 and 2 indicates that it is possible to use results derived at stage 3 as etalon results (similarly to [9], [11]).

4.3 Validation Results

Validation of the worst-case model was made at the following values of parameters: radiation frequency is 300 kHz1.2 GHz (for balanced terminations), 10 MHz1.2 GHz (for unbalanced terminations); distance from the observation point (placed above the ground plane) to center of the twisted pair is 4 cm2 m (for balanced and unbalanced terminations) in an arbitrary direction, l=1 m, h=0.02 m, $r_{1,2}$=2.5 mm, r_w=0.56 mm, ε_1=2.3, n=50, parameters of the source and the load for the case of balanced terminations: E=1 V, R_S=5 Om, L_S=1 nH, C_S=1 pF, 1 nF, R_L= 50 Ohm, L_L=1 H, C_L=1 pF, 1 nF, for the case of unbalanced terminations: E=1 V, R_S=50 Ohm, L_S=1 H, C_S=1 nF, R_L= 50 Ohm, L_L=1 H, C_L=1 nF.

Comparison example of electric and magnetic field AFC computation results for the worst-case model and for etalon derived by the approximate method (see Subsection 4.1) is shown at Figure 5 (in case of ideally balanced terminations, $I_c/I_d = 0$). Comparison example of electric and magnetic field AFC computation results for the worst-case model and for the etalon (see Subsection 4.2) in case of unbalanced termination is shown at Figure 6. The red line corresponds to computation results of etalon AFC at the stage 1, the green line corresponds to the stage 2, and the blue line corresponds to the

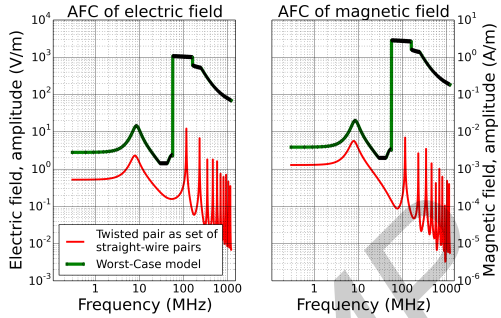


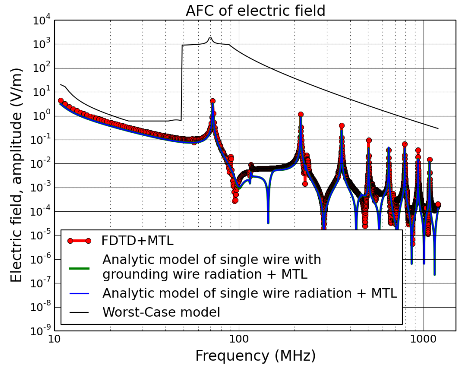
Figure 5: Validation of the worst-case model for twisted-pair radiation in case of balanced terminations. Parameters of the problem: observation point (0.25 m; 0; 0.04 m), E=1 V, l=1 m, h=0.02 m, $r_{1,2}$=2.5 mm, r_w=0.56 mm, ε_1=2.3, R_S=5 Ohm, L_S=1 nH, C_S=1 nF, R_L= 50 Ohm, L_L=1 H, C_L=1 nF, n=50.

stage 3. AFC computation results by the worst-case model are presented by the black line.

Validation results confirm the worst-case nature of the twisted pair radiation model proposed in Section 3. Using of methods of currents [10] and fields [9] calculation having high computational efficiency and analytic account for the twisted pair radiation peculiarities (see Section 3) explain high computational efficiency of the developed model. Average calculation time of one AFC point for computer having processor AMD FX(tm)-4100 Quad-Core and RAM type DDR3-1333 is 0.15 ms.

5 Conclusion

The developed worst-case model of twisted pair radiation can be used for diagnostics (express-analysis) of EMC between on-board radio-electronic equipment of big systems: cars, aircrafts, ships, etc. [2], [3]. Frequency range of the proposed model (300 kHz to 1.2 GHz) is restricted by capabilities of numerical methods used for its validation. Possible ways of the model improvement are as follows: to account for slots in the ground plane and for finite dimensions of the ground plane, to introduce shields around the twisted pair, and to account for inherent resonances of the board system hull on the basis of its characteristic dimensions and equivalent Q-factor.



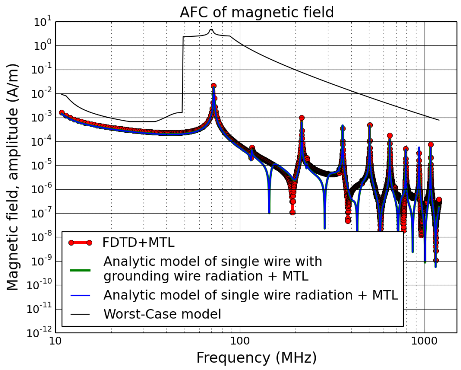


Figure 6: Validation of the worst-case model for twisted-pair radiation in case of unbalanced terminations. Parameters of the problem: observation point (-0.25 m; 0; 0.04 m), E=1 V, l=1 m, h=0.02 m, $r_{1,2}$=2.5 mm, r_w=0.56 mm, ε_1=2.3, R_S=50 Ohm, L_S=1 H, C_S=1 nF, R_L= 50 Ohm, L_L=1 H, C_L=1 nF, n=50.

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