Comparison of Analysis, Simulation, and Measurement of Wire-to-Wire Crosstalk, Part 1

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Abstract—In this investigation, we compare crosstalk analysis, simulation, and measurement results for electrically short configurations. Methods include hand calculations, PSPICE simulations, Microstripes transient field solver, and empirical measurement. In total, four representative physical configurations are examined, including a single wire over a ground plane, a twisted pair over a ground plane, generator plus receptor wires inside a cylindrical conduit, and a single receptor wire inside a cylindrical conduit. Part 1 addresses the first two cases, and Part 2 addresses the final two. Agreement between the analysis, simulation, and test data is shown to be very good.

I. INTRODUCTION
Crosstalk is the unintended electromagnetic coupling between wires in close proximity. It is dependent on many factors including wire type, physical dimensions, spacing, surrounding materials, field type and levels, and frequencies. For electrically short wires, crosstalk can be modeled using simple lumped circuit analysis as well as more general transmission line techniques (1). It can also be simulated using transient field solver programs, such as Microstripes.

In this investigation, four different wire configurations were examined, including a single wire over a ground plane, a twisted pair over a ground plane, two wires (generator plus receptor) inside a cylindrical conduit, and a single receptor wire inside a cylindrical conduit. The first two configurations are examined in this paper. The final two are examined in the Part 2 publication (also included in the proceedings of the 2010 Asia Pacific EMC Symposium). Hand calculations, simulations, and experimental results were compared and shown to agree very well.

As shown in Fig. 1, the crosstalk system consisted of a generator circuit (i.e. source wire) and a receptor circuit (i.e. victim wire). The generator circuit remained a simple single wire conductor over a ground plane, a twisted pair over a ground plane, two wires (generator plus receptor) inside a cylindrical conduit, and a single wire inside a cylindrical conduit. The first two configurations are examined in this paper. The final two are examined in the Part 2 publication (also included in the proceedings of the 2010 Asia Pacific EMC Symposium). Hand calculations, simulations, and experimental results were compared and shown to agree very well.

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wires over a large conductive sheet. An HP8657B signal generator was used to generate the stimulus $V_s$. Measurements were taken using an Agilent E4401B spectrum analyzer and LeCroy AP034 active differential probe.

### A. Hand Calculations

As with each configuration, the system was first modeled using per-unit-length capacitances and inductances (both self and mutual). This served as a distributed lumped model representation of the electromagnetic coupling and offered a straightforward method by which to perform hand calculations and PSPICE simulations.

The expression for the voltages at each end of the receiving circuit are given by (1) and (2), where $L_m$ and $C_m$ are the mutual inductance and capacitance between wires. The first terms in each equation represent the inductive coupling (through loop antenna magnetic field action), and the second terms represent the capacitive coupling (through wire antenna electric field action) as discussed in [1].

\[
V_{\text{NE}} = \frac{R_{\text{NE}}}{R_{\text{NE}} + R_{\text{FE}}} \cdot \frac{1}{R_s + R_L} V_s + \frac{R_{\text{NE}} R_{\text{FE}}}{R_{\text{NE}} + R_{\text{FE}}} \cdot j \omega C_m \quad (1)
\]

\[
V_{\text{FE}} = -\frac{R_{\text{FE}}}{R_{\text{NE}} + R_{\text{FE}}} \cdot \frac{1}{R_s + R_L} V_s + \frac{R_{\text{NE}} R_{\text{FE}}}{R_{\text{NE}} + R_{\text{FE}}} \cdot j \omega C_m \quad (2)
\]

Total values for $C_m$ and $L_m$ were found by first determining the per-unit-length circuit parameters and then multiplying them by the wire length. The per-unit-length inductances and capacitances for the single wire case are given by (3)-(8) as outlined in [1].

\[
l_0 = \frac{\mu_0}{2\pi} \cdot \ln \left( \frac{2h_c}{r_w} \right) \quad (3)
\]

\[
l_1 = \frac{\mu_0}{2\pi} \cdot \ln \left( \frac{2h_s}{r_w} \right) \quad (4)
\]

\[
l_m = \frac{\mu_0}{4\pi} \cdot \ln \left( 1 + \frac{4h_s h_c}{s^2} \right) \quad (5)
\]

Where $\mu_0 = 4\pi \times 10^{-9}$ Tm/A is the permeability of free space, $h_i$ is the height of the respective wire above the ground plane, $r_w$ is the radius of a wire, $s$ is the separation distance of the wires, $\omega$ is the angular frequency, and $v$ is the velocity of propagation ($3 \times 10^8$ m/s in free space).

### B. Simulations

Simulations were completed using both PSPICE and CST’s Microstripes—a time-domain field solver that uses the transmission line matrix (TLM) method. That method “meshes” the physical model in three dimensions and treats each piece as a transmission line structure.

The per-unit-length circuit model parameters calculated for hand calculations were also fed directly into PSPICE, given as Fig. 3. The inductive coupling between generator and receptor circuits was achieved using the PSPICE K-Coupling element. Capacitive coupling was achieved through the inclusion of $C_m$.

![Fig. 3 PSPICE single-wire model](image)

Microstripes was used to generate a 3D representation of the crosstalk assembly as shown in Fig. 4. The software allows the importing of CAD files or the direct drawing of physical systems. Geometries as well as the electromagnetic properties of all materials were considered during simulation.

![Fig. 4 Microstripes model](image)

### C. Results

For the single wire case, the results obtained from all four methods (experimentation, hand calculations, PSPICE, and
Microstripes) were all in excellent agreement. Fig. 6 and Fig.
7 show the magnitude of \( V_{NE} \) and \( V_{FE} \) for the case when \( R_L \)
was varied, and \( R_{NE} \) and \( R_{FE} \) were held constant at 511Ω.
As can be seen from both graphs, there are three regions of
crosstalk coupling. In the first region, \( R_L \) is small, and the
inductive coupling acts as the primary crosstalk mechanism.
The inverse relation between generator current and load
resistance causes both the near- and far-end crosstalk voltages
to decrease with increasing \( R_L \). As \( R_L \) further increases in
value, a point is reached where \( V_{FE} \) essentially goes to zero as
inductive and capacitive coupling cancel. The near-end
voltage on the other hand is simply the sum of the capacitive
and inductive terms. Finally, in the final region, \( R_L \) becomes
large enough that the capacitive term becomes the dominant
coupling mechanism. This causes \( V_{NE} \) and \( V_{FE} \) to approach a
constant value as can easily be seen from (1) and (2).

Fig. 8 and Fig. 9 show the results obtained when \( R_{NE} \) and
\( R_{FE} \) were varied for a constant \( R_L \), again arbitrarily chosen to
be 511Ω. For simplicity, \( R_{NE} \) and \( R_{FE} \) were kept equal as they
were increased. The four methods once again generally agreed
quite well. Inductive coupling is the dominant mechanism for
low values of \( R_{NE} \) and \( R_{FE} \). For higher values of impedance,
capacitive coupling dominates. When increasing \( R_{NE} \) and \( R_{FE} \),
the near-end crosstalk voltages increase as expected from (1).
Far-end crosstalk initially decreases (negative slope) due to
the cancelation between inductive and capacitive terms. Beyond that point, the slope turns positive as capacitive
coupling dominates.

The trends are more intuitive when considering the simple
circuit model of Fig. 1. Capacitive coupling, modeled as a
constant current source, acts to inject a current into an
increasing receptor impedance. This results in an increasing
coupled voltage (at both ends). Likewise, for our case of a
constant \( R_L \) and equal \( R_{NE} \) and \( R_{FE} \) resistors, inductive
coupling remains constant and is modeled as a constant series
voltage source.

III. TWISTED PAIR CONFIGURATION

For the second test case, the receptor wire was twisted with
a return wire and grounded only at the near end. A single
generator wire was routed parallel to the twisted pair. This
setup was designed to emulate a real-world system in which a
signal is sent to an external isolated load using twisted pair
wiring.

Fig. 5 Twisted Pair setup
The per-unit-length inductances and capacitances were once again calculated with equations presented in [1]. The near- and far-end voltages are then given by (9) and (10).

\[
V_{\text{NE}} = \left[ \frac{R_{\text{NE}}}{R_{\text{NE}} + R_{\text{FE}}} \right] \frac{\alpha (\omega l_{\alpha 2}) L_{\text{HT}}}{R_s + R_L} \frac{1}{R_{\text{NE}}} \frac{1}{R_{\text{FE}}} + \left[ \frac{R_{\text{NE}} R_{\text{FE}}}{R_{\text{NE}} + R_{\text{FE}}} \right] \frac{R_s}{R_s + R_L} V_s \right]
\]

(9)

\[
V_{\text{FE}} = \left[ \frac{R_{\text{NE}}}{R_{\text{NE}} + R_{\text{FE}}} \right] \frac{\alpha (\omega l_{\alpha 2}) L_{\text{HT}}}{R_s + R_L} \frac{1}{R_{\text{NE}}} \frac{1}{R_{\text{FE}}} + \left[ \frac{R_{\text{NE}} R_{\text{FE}}}{R_{\text{NE}} + R_{\text{FE}}} \right] \frac{R_s}{R_s + R_L} V_s \right]
\]

(10)

The PSPICE model is given as Fig. 10.

From basic field theory, one would expect a reduction in crosstalk due to the use of a dedicated return wire. With a smaller primary current loop area, the total magnetic flux coupled into the receptor circuit is greatly reduced. Furthermore, there is an additional decrease in magnetic field coupling due to the alternating polarity of each loop. Induced voltages in one loop would be expected to cancel out the induced voltages in the adjacent loop.

The results of the twisted pair case were again consistent between calculations, simulations, and experimentation. Also as expected, the data revealed that the use of a twisted dedicated return greatly reduced inductive coupling. Fig. 11 and Fig. 12 show that for a fixed $R_{\text{NE}}$ and $R_{\text{FE}}$, all that remains is the modest level of capacitive coupling. Likewise, Fig. 13 and Fig. 14 show the expected positive trend without the earlier dip seen as a result of inductive-capacitive cancellation.

IV. SUMMARY

In this first part, crosstalk into a single wire above a ground plane and into twisted pair wiring was examined. For both cases, hand calculations, PSPICE, Microstrips, and empirical data agreed very well. Additional cases are examined in Part 2.

V. REFERENCES

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