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Maximum Radiated Emission Calculator: I/O Coupling Algorithm

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Abstract

The Maximum Radiated Electromagnetic Emissions Calculator (MREMC) is a software tool that allows the user to calculate the maximum possible radiated emissions that could occur due to specific source geometries on a printed circuit board. This report describes the I/O coupling algorithm, which determines the maximum possible radiated emissions that could occur due to coupling from a source signal on one trace to another (I/O) trace that could carry the coupled signal off the board. The methods used, calculations made, and implementation details are described.

1. Introduction

High frequency signals on one circuit board trace can couple to input/output (I/O) traces that carry the coupled energy away from the board. The common-mode currents induced on cables attached to I/O nets can result in significant radiated emissions. The I/O coupling EMI calculator was developed to calculate the maximum possible radiated emissions from structures like this. The calculator utilizes formulas for crosstalk between PCB traces described by Gupta [4] and expressions for the maximum radiated emissions from PCB-cable structures developed by Deng [2]. This report is an extension of the method described by Su [1] and is intended to provide details of the implementation sufficient to allow others to develop their own version of this calculator.

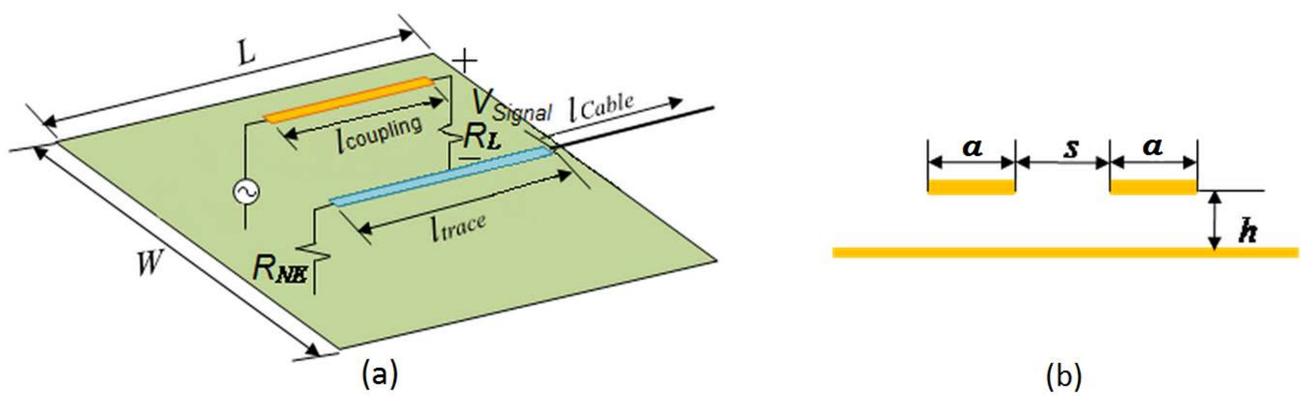

Fig. 1. I/O Coupling model: (a), top view, (b), section view.

Two parallel sections of microstrip circuit board traces are illustrated in Fig. 1. The cross-sectional view in Fig. 1(b) shows that both traces have a width, a, a height, h, and edge-to-edge separation, s. The board length, L, board width, W, relative dielectric constant, ε_r, coupling length, $l_{coupling}$, and I/O trace length, l_{trace}, are the other geometrical parameters required for this calculation. V_{Signal} and R_L represent the signal source voltage and the load resistance of the signal trace respectively. R_{NE} is the near end resistance of the I/O trace. The I/O cable length is unspecified, but board is assumed to be 1 meter over a ground plane, as it would be in most radiated emissions tests [2].

The calculator calculates the maximum radiated electric field at a distance of 3 meters from the board and plots the results in $dB\mu V/m$ from 0 to 100 MHz as shown in Fig. 2.

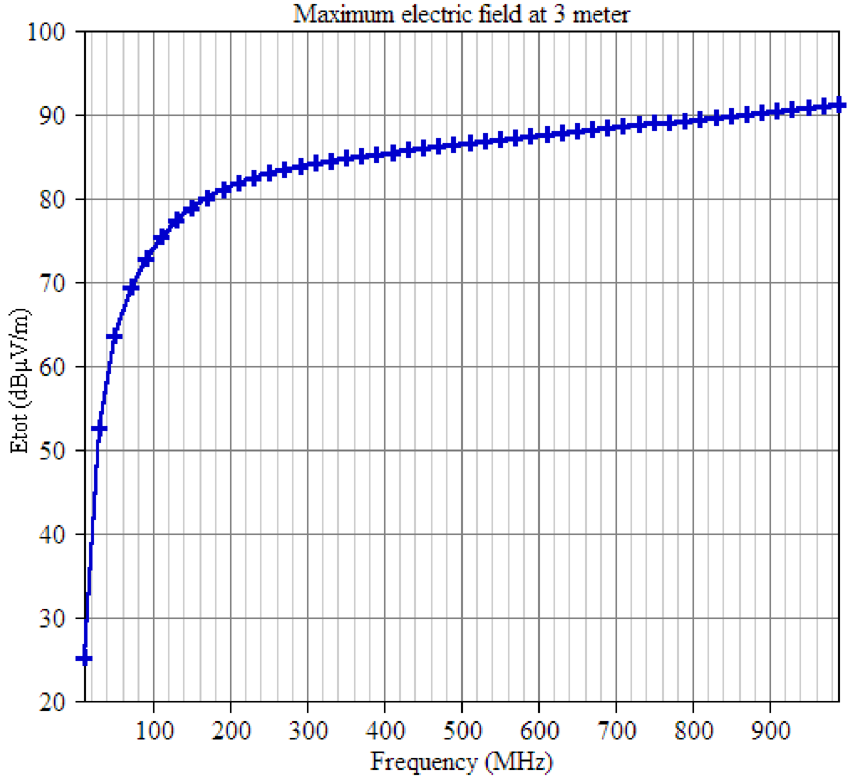

Fig. 2 MREMC plot example.

2. Description of Algorithm

The algorithm used by the calculator can be broken into two main parts. The first is to determine the equivalent common-mode (CM) source based on the trace geometry. The second is to determine the maximum radiated emissions based on the CM source and cable-board geometry. To determine the CM source, the total voltage coupled to the victim circuit is determined by the *coupling* algorithm and the *Thevenin equivalent* algorithm. After the CM source is obtained, the maximum radiated emissions are then estimated by the *estimation* algorithm.

2.1 The Coupling Algorithm

2.1.1 I/O coupling model

Fig. 3(a) shows the coupling model, which can be represented more simply as shown in Fig. 3(b). V_S, Z_L and Z_{NE} are the same as V_S, R_L and R_{NE} indicated in Fig. 1. Note that in this calculator, Z_L and Z_{NE} only support resistive input. Z_{FE} is the far-end load of the I/O trace, representing the input impedance of the antenna formed by the I/O cable being driven against the wide PCB ground plane. L_m represents the mutual inductance between the two trace-ground loops. C_m represents the mutual capacitance between the two traces. Inductive coupling occurs when changing current in the signal trace induces a voltage on the I/O trace through L_m. Similarly, the capacitive coupling occurs when a changing voltage on the signal trace induces a current on the I/O trace through C_m.

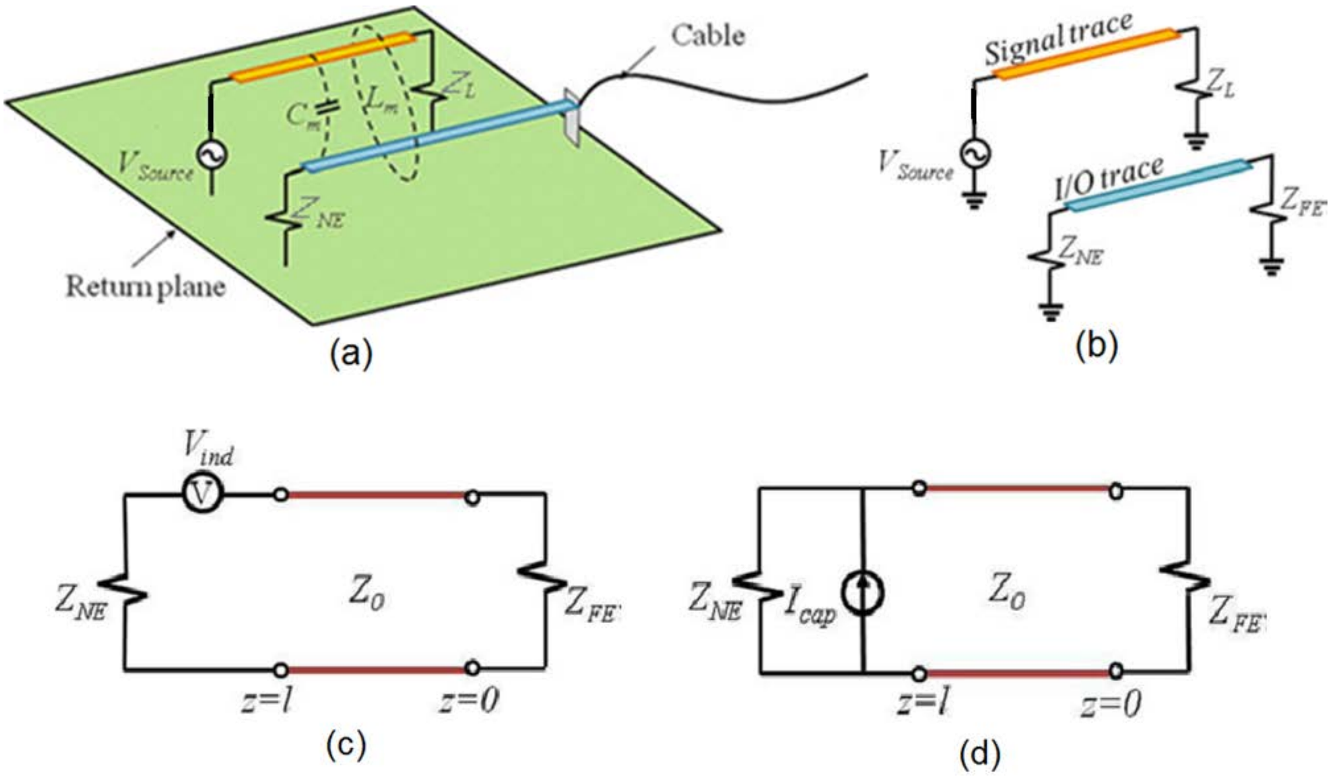

Fig. 3 Coupling algorithm: (a), coupling model, (b), simplified model, (c), inductive coupling schematic, (d), capacitive coupling schematic.

2.1.2 Inductive Coupling

Fig. 3(c) is the lumped-element circuit model for the inductive coupling. The I/O trace and return plane are represented as a transmission line of length *l*. V_{ind} represents the induced electromotive force due to inductive coupling, which is given by

$$V_{ind} = -j\omega L_m I_{source} \tag{1}$$

where I_{source} is the current on the signal which can be obtained by V_{Signal} / Z_L. Note that the self inductance of the signal trace loop is ignored since at a frequency where the loop inductance matters, the trace usually has a matched load. In the subroutine *calcEM()*, only the magnitude of the V_{ind} is calculated,

$$|V_{ind}| = 2\pi f L_m I_{source}\,. \tag{2}$$

2.1.3 Capacitive Coupling

Fig. 3(d) is the lumped-element circuit model for the capacitive coupling. An independent current source, I_{cap} , represents the induced current due to capacitive coupling, which is given by

$$I_{cap} = j\omega C_m V_{\text{signal}} \approx j\omega C_m Z_L I_{source}\,. \tag{3}$$

In the subroutine *calcEM()*, only the magnitude of the I_{cap} is calculated. Then magnitude of V_{cap} is obtained by

$$|V_{cap}| = |I_{cap}| \bullet Z_{NE} = 2\pi f C_m Z_L Z_{NE} I_{source}\,. \tag{4}$$

2.1.4 Total Coupling

Assuming the lines are weakly coupled, the maximum possible coupling is a linear combination of contributions due to the inductive and capacitive coupling [3]. The maximum voltage induced in the victim circuit is the sum of the two coupled voltages,

$$|V_{total}| = |V_{ind} + V_{cap}| = |j\omega[-L_m + C_m Z_L Z_{NE}] I_{source}| = ||V_{ind}| + |V_{cap}|| . \quad (5)$$

2.1.5 Mutual Inductance and Capacitance

The mutual inductance L_m and mutual capacitance C_m are required to calculate the induced voltages. The subroutine *calcMutual()* calculates L_m and C_m by [4]

$$C_m = \frac{1}{2}[C_o(\varepsilon_r) - C_e(\varepsilon_r)] \bullet l_{coupling} \quad (6)$$

$$L_m = \frac{\mu_0 \varepsilon_0}{2}\left[\frac{1}{C_e(\varepsilon_r = 1)} - \frac{1}{C_o(\varepsilon_r = 1)}\right] \bullet l_{coupling} \quad (7)$$

where C_o and C_e are even and odd mode capacitances per unit length respectively. $l_{coupling}$ is the coupling length for user input. (6) and (7) only apply to symmetrical traces (traces with same width) [4]. For coupled microstrip lines, the components of the line capacitance are illustrated in Fig. 4. The algorithms to calculate are C_o and C_e are included in the subroutine *calcCeCo(epsr)*.

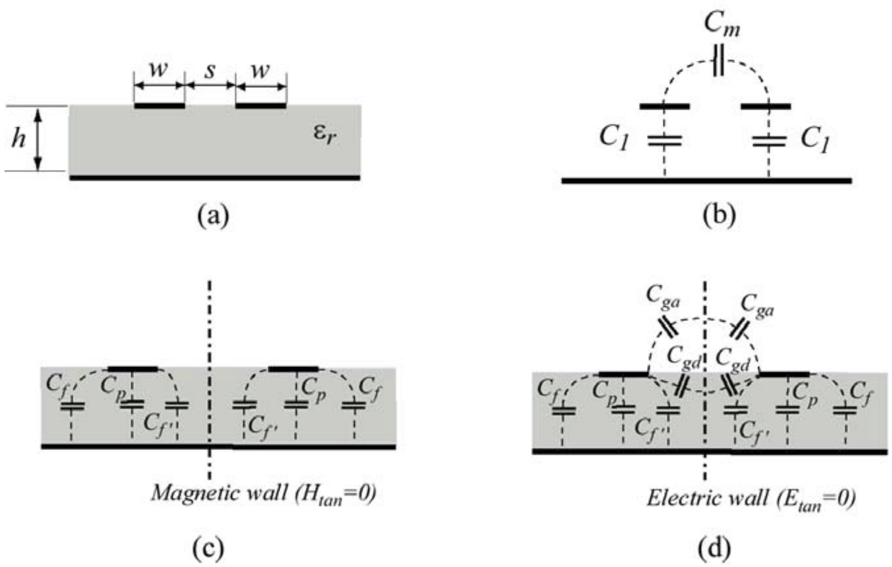

Fig. 4 Configuration of coupled microstrip line (a), general equivalent circuit (b), and breakup of even mode (c) and odd mode (d) capacitance

For the even mode, the capacitance C_e is given as [4],

$$C_e(\varepsilon_r) = C_p + C_f + C_{f'} \quad (8)$$

where,

$$C_p = \frac{\varepsilon_0 \varepsilon_r w}{h} \quad (9)$$

$$C_f = \frac{1}{2}\left[\frac{\sqrt{\varepsilon_r}}{cZ_0} - C_p \right] \tag{10}$$

$$C_{f'} = \frac{C_f \bullet \sqrt[4]{\varepsilon_r / \varepsilon_{re}}}{1 + A(h/s)\tanh(10s/h)} \tag{11}$$

where,

$$A = \exp\left[-0.1\exp(2.33 - 1.5w/h) \right] \tag{12}$$

$$Z_0 = \begin{cases} \dfrac{120\pi}{2\pi\sqrt{\varepsilon_{re}}}\ln(8h/w + 0.25w/h) & w/h \le 1 \\ \dfrac{120\pi}{\sqrt{\varepsilon_{re}}}\left[w/h + 1.393 + 0.667\ln(w/h + 1.444) \right]^{-1} & w/h > 1 \end{cases} \tag{13}$$

where ε_{re} is effective relative permittivity, which can be found by [5],

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12h/a}}\,. \tag{14}$$

The values are found to be accurate to within 3 percent, compared with the values obtained from [6], over the following range of parameters [4],

$$0.1 \le w/h \le 10 \qquad 0.1 \le s/h \le 5 \qquad 1 \le \varepsilon_r \le 18$$

For the odd mode, the capacitance C_o is found by [4],

$$C_e(\varepsilon_r) = C_p + C_f + C_{f'} + C_{ga} + C_{gd} = 0.5C_{os} + C_{cps} \tag{15}$$

where,

$$C_{cps} = \varepsilon_0 \frac{K(k')}{K(k)} \tag{16}$$

$$C_{os} = 4\varepsilon_0\varepsilon_r \frac{K(k_0)}{K(k_0')} \tag{17}$$

where,

$$k = \frac{s}{s + 2w} \tag{18}$$

$$k' = \sqrt{1 - k^2} \tag{19}$$

$$k_0 = \tanh\left(\frac{\pi w}{4h} \right)\coth\left[\frac{\pi}{4}\left(\frac{w + s}{h} \right) \right] \tag{20}$$

$$k_0' = \sqrt{1 - k_0^{\ 2}}\,. \tag{21}$$

The function $K(k)$ and $K(k')$ are the complete elliptic function and its complement and their ratio is given by

$$\frac{K(k')}{K(k)} = \begin{cases} \frac{1}{\pi}\ln\left(2\frac{1+\sqrt{k'}}{1-\sqrt{k'}}\right) & 0 \le k \le \frac{1}{\sqrt{2}} \\ \pi \Big/ \ln\left(2\frac{1+\sqrt{k}}{1-\sqrt{k}}\right) & \frac{1}{\sqrt{2}} \le k \le 1 \end{cases} . \tag{22}$$

Same applies to $K(k_0)$ / $K(k_0')$

The capacitances obtained by using the above equations are accurate within 3 percent, compared with values obtained from [6], over the range of parameters [4],

$$0.1 \le w/h \le 10 \qquad 0.1 \le s/h \le 4 \qquad 2 \le \varepsilon_r \le 18$$

2.2 Thevenin Equivalent Algorithm

A Thevenin equivalent source model was derived to account for all of the coupling without requiring the input impedance of the attached cable to be known. The I/O trace may or may not be electrically short and is modeled as a transmission line as indicated in Fig. 5(a). The open-circuit voltage at the far end (i.e., the connector) V_{eq}, and the equivalent impedance looking back toward the near end from the connector Z_{eq}, can be readily calculated from transmission line theory yielding the Thevenin equivalent circuit in Fig. 5(b).

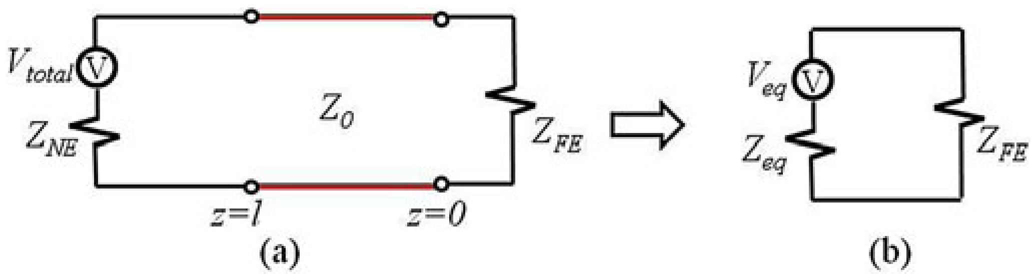

Fig. 5 Thevenin equivalent model

V_{eq} and Z_{eq} can be found by [1]

$$\mathrm{V}_{eq} = 2\left(\frac{Z_0}{Z_0 + j\mathrm{Z}_{\mathrm{NE}}\tan\beta l}\right)\left(\frac{V_{total}}{e^{j\beta l} + e^{-j\beta l}}\right) \tag{23}$$

$$\mathrm{Z}_{eq} = Z_0\left(\frac{\mathrm{Z}_{\mathrm{NE}} + jZ_0\tan\beta l}{Z_0 + j\mathrm{Z}_{\mathrm{NE}}\tan\beta l}\right) \tag{24}$$

where Z_0 is the characteristic impedance of the transmission line, which is given in (13) and βl is the wavenumber, which is given by

$$\beta l = \frac{2\pi f l_{trace}\sqrt{\varepsilon_r}}{c_0} . \tag{25}$$

In the subroutine *calcEM()*, the magnitude of V_{eq}, the real part of Z_{eq} and the imaginary part of Z_{eq} are calculated separately by

$$\left|\mathrm{V}_{eq}\right| = \left(\frac{Z_0}{\sqrt{Z_0^{\ 2} + \left(\mathrm{Z}_{\mathrm{NE}} \tan \beta l\right)^2}} \right) \left(\frac{V_{total}}{\left|\cos \beta l\right|} \right) \tag{26}$$

$$\mathrm{Z}_{eq.\mathrm{real}} = \frac{\mathrm{Z}_0^{\ 2} Z_{NE} + \mathrm{Z}_0^{\ 2} Z_{NE} \left(\tan \beta l\right)^2}{Z_0^{\ 2} + \left(\mathrm{Z}_{\mathrm{NE}} \tan \beta l\right)^2} \tag{27}$$

$$\mathrm{Z}_{eq.imag} = \frac{\mathrm{Z}_0^{\ 3} \tan \beta l - \mathrm{Z}_0 Z_{NE}^{\ 2} \tan \beta l}{Z_0^{\ 2} + \left(\mathrm{Z}_{\mathrm{NE}} \tan \beta l\right)^2} \tag{28}$$

Fig. 3(a) can then be replaced by the model in Fig. 6 with the Thevenin equivalent source voltage and impedance. The new model is ready for use in the radiated emission estimation.

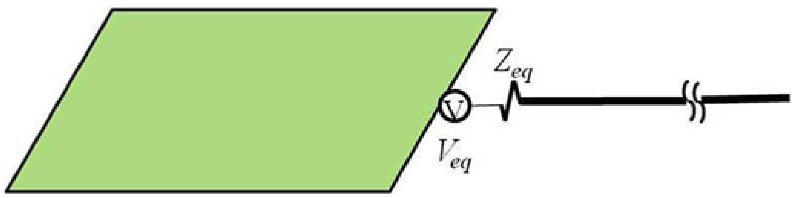

Fig. 6 I/O coupling model with CM source and impedance

2.3 Maximum Radiated Emission Estimation Algorithm

2.3.1 Board-source-cable geometry

A simplified geometry representing a typical EMC test environment is shown in Fig. 7, where the PCB board is 1m above the ground. Study in [2] suggests that the peak emissions from such geometry are relatively independent of the connection point to the board and relatively insensitive to the total cable length or orientation. The parameters that matter are the vertical distance traversed by the cable and the maximum current. Also the maximum radiated electric field for this geometry can be estimated by comparing the emissions from this structure to the emissions from a thin-wire monopole above an infinite ground plane. In [2], a closed-form formula was developed to estimate the maximum radiated emissions from the antenna model in Fig. 7. This formula was enhanced in [7] to be more accurate over the larger frequency ranges.

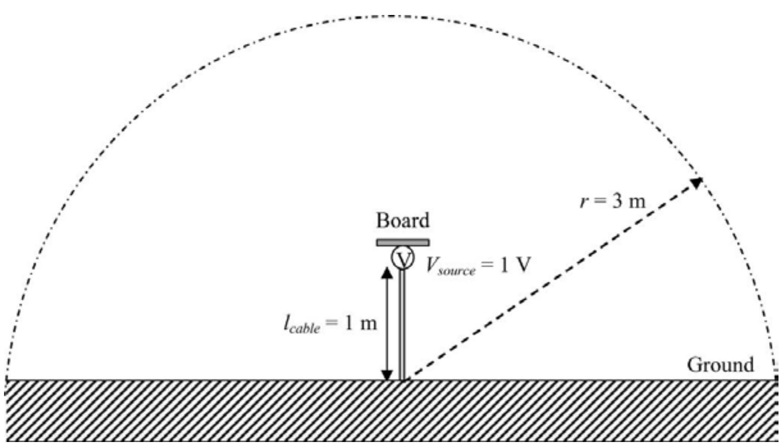

Fig. 7 Board-source-cable geometry

2.3.2 Maximum Radiated Emission Estimation

In subroutine *calcEM()*, the maximum electric field at 3m as shown in Fig. 6 is calculated by [2],

$$\left|E\right|_{\max} = 20 \times I_{peak} \times f(\theta, k, l_{cable}) \tag{29}$$

where $f(\theta, k, l_{cable})$ can be obtained by [7],

$$f(\theta, k, l_{cable}) = \begin{cases} \dfrac{2}{\sin\left(\sqrt{2}\right)} & \mathrm{f} \le \dfrac{c_0}{2 l_{cable}} \\ \dfrac{2}{\sin\left(\sqrt{\dfrac{c_0}{f l_{lable}}}\right)} & \mathrm{f} > \dfrac{c_0}{2 l_{cable}} \end{cases} \tag{30}$$

where l_{cable} is the length of the attached cable, which is set to 1m in the calculator. f is the frequency, and c0 is the propagation velocity in free space. The equation is calculated in subroutine *finFmax()*. I_{peak} is the highest current that actually exists on the cable and is given by

$$I_{peak} = \frac{V_{eq}}{\left| Z_{eq} + \dfrac{R_{\min}}{board\_factor \times cable\_factor} \right|} \tag{31}$$

where R_{min} is the input resistance (about 37 Ω) of a resonant quarter-wave monopole. Two factors account for the effect that the finite cable length and the small board size have on this minimum resistance, which are given by,

$$board\_factor = \begin{cases} \sin\left(2\pi \, \mathrm{l_{board}} / \lambda\right) & when \quad l_{board} \le \dfrac{\lambda}{4} \\ 1.0 & otherwise \end{cases} \tag{32}$$

$$cable\_factor = \begin{cases} \sin\left(2\pi \, \mathrm{l}_{cable} / \lambda\right) & when \quad l_{cable} \le \dfrac{\lambda}{4} \\ 1.0 & otherwise \end{cases} \tag{33}$$

where l_{board} is the effective length of a rectangular board. It can be approximated as,

$$l_{board} = \frac{1 + {2L}/{\mathrm{W}}}{{2L}/{W}} \times \sqrt{L^2 + W^2} \tag{34}$$

where *L* and *W* denote the board length and width, respectively as shown in Fig. 1.Equation 31 is then calculated in subroutine *calcEM()* as,

$$I_{peak} = \frac{V_{eq}}{\sqrt{\left(Z_{eq.real} + \dfrac{37}{board\_factor \times cable\_factor} \right)^2 + Z_{eq.\mathrm{imag}}{}^2}}. \tag{35}$$

2.4 Assumptions Made in this Derivation

1. Signal trace and I/O trace are weakly coupled.

   The induced currents and voltages in the victim circuit will induce currents and voltages back into the generator circuit. By assuming weak coupling, the currents and voltages coupled back into the generator circuit are ignored. [3]

2. Portion of the signal trace coupling to the I/O line is electrically short with a self-capacitance and self-inductance that are negligible compared to the source and load impedances. This is frequently the case, but similar equations that do not depend on the value of Z_{FE} could be readily derived for longer signal traces. [1]

3. The I/O trace can be model as a lossless transmission line, which is a reasonable approximation.

4. The attached cable has negligible diameter, which is a good approximation when the cable diameter is considerably smaller than the wavelength.

2.5 Limitations Due to Implementation

1. These calculations are designed for symmetric microstrip lines.
2. The coupling algorithm provides reasonably accurate values in the following range, $0.1 \le w/h \le 10 \quad 0.1 \le s/h \le 4 \quad 2 \le \varepsilon_r \le 18$
3. The Estimation algorithm currently calculates emissions for a typical EMC test environment with the EUT set 1 meter above the ground and the measuring antenna located 3 meters away.

3. Conclusion

This calculator determines the maximum possible radiated emissions due to coupling from a signal trace to an I/O trace on a circuit board. It is limited to symmetric microstrip lines and assumes that the length of the coupled section is small relative to a wavelength at the highest frequency of the analysis. Applied to longer coupled sections, the calculator will overestimate the possible radiated emissions.

References

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[4] K. Gupta, R. Garg, I. Bahl, and P. Bhartia, *Microstrip Lines and Slotlines, 2nd ed.*, Norwood, Artech House, 1996, ch 8, pp 457-516.

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[6] M. Kirschning and R. H. Jansen, "Accurate Wide-Range Design Equations for the Frequency-Dependent Characteristics of Parallel Coupled Microstrip Lines (Corrections)," *IEEE Transactions on Microwave Theory and Techniques*, vol.33, no.3, p. 288, Mar 1985.

[7] C. Su and T. H. Hubing, "Improvements to a Method for Estimating the Maximum Radiated Emissions From PCBs With Cables," *IEEE Transactions on Electromagnetic Compatibility*, vol. 53, pp. 1087-1091, Nov 2011.

Appendix (Java codes)

The java codes contain all the subroutines are list below.

1. Subroutine calcCeCo(epsr)

```
function calcCeCo(epsr){
        var carray=new Array();
        var epsre=(epsr+1)/2+(epsr-1)/2*Math.pow(1+12*t/a,-0.5);  //Eq. 14
        var z0;
        if (a<=t){
                z0=60/Math.sqrt(epsre)*Math.log(8*t/a+0.25*a/t);
        }
        else{
                z0=120*pi/(epsre)/(a/t+1.393+0.667*Math.log(a/t+1.444));
        } //Eq. 13
        var A=Math.exp(-0.1*Math.exp(2.33-1.5*a/t));  //Eq. 12
        var cp=eps0*epsr*a/t;  //Eq. 9
        var cf=1/2*(Math.sqrt(epsr)/c0/z0-cp);  //Eq. 10
        var x=10*s/t;
        var tanhx=(Math.exp(x)-Math.exp(-1*x))/(Math.exp(x)+Math.exp(-1*x));
        var cfp=cf*Math.pow(epsr/epsre,0.25)/(1+A*t/s*tanhx);  //Eq. 11
        carray[0]=cp+cf+cfp;  // Eq. 8
        var k=s/(s+2*a); //Eq. 18
        var kp=Math.sqrt(1-k*k); //Eq. 19
        if (k<(1/Math.sqrt(2)))
                var Ccps=eps0/pi*Math.log(2*(1+Math.sqrt(kp))/(1-Math.sqrt(kp)));
        else
                var Ccps=eps0*pi/Math.log(2*(1+Math.sqrt(k))/(1-Math.sqrt(k)));  //Eq. 16
        x=pi/4*(s+a)/t;
        var cothx=(Math.exp(x)+Math.exp(-1*x))/(Math.exp(x)-Math.exp(-1*x));
        x=pi*a/4/t;
        tanhx=(Math.exp(x)-Math.exp(-1*x))/(Math.exp(x)+Math.exp(-1*x));
        var ko=tanhx*cothx;  //Eq. 20
        var kop=Math.sqrt(1-ko*ko);  //Eq. 21
        if (ko<(1/Math.sqrt(2)))
                var Cos=4*eps0*epsr/pi*Math.log(2*(1+Math.sqrt(ko))/(1-Math.sqrt(ko)));
        else
                var Cos=4*eps0*epsr*pi/Math.log(2*(1+Math.sqrt(kop))/(1-Math.sqrt(kop))); //Eq. 17
        carray[1]=Ccps+0.5*Cos;  //Eq. 15
        return carray;
}
```

1.1 Subroutine calcMutual()

```
function calcMutual(){
        var carray=calcCeCo(epsr);
        cm=0.5*(carray[1]-carray[0])*lcoupling;  // Eq. 6
        cs=0.5*(carray[1]+carray[0])*lcoupling;
        carray=calcCeCo(1);
        lm=mu0*eps0/2*(1/carray[0]-1/carray[1])*lcoupling;  //Eq. 7
        ls=mu0*eps0/2*(1/carray[0]+1/carray[1])*lcoupling;  //Eq. 24
}
```

1.2 Subroutine findFmax(f)

```
function findFmax(f){
        var temp=c0/2/lcable;
        if (f<=temp)
                ffmax=2/Math.sin(Math.sqrt(2));
        else
```

```
            ffmax=2/Math.sin(Math.sqrt(c0/(f*1e6)/lcable)); //Eq. 30
    }
```

1.3 Subroutine calcEM()

```
    function calcEM(){
        calcMutual();
        zl=document.getElementsByName("tparr[0]").item(0).value;
        zne=document.getElementsByName("tparr[1]").item(0).value;
        var vind,vcap;
        var vtotal=new Array();
        for (i=0;i<vdm.length;i++){
            vind=2*pi*x[i]*1e6*lm*vdm[i]/zl;  //Eq.2
            vcap=2*pi*x[i]*1e6*cm*vdm[i]*zne;  //Eq.4
            vtotal[i]=Math.abs(vind-vcap);  //Eq. 5
        }
        var z0;
        if (a<=t)
            z0=60*Math.log(8*t/a+a/4/t);
        else
            z0=120*pi/(a/t+1.393+0.667*Math.log(a/t+1.444)); //Eq. 13
        var lboard=(1+2*l/w)/(2*l/w)*Math.sqrt(l*l+w*w);  //Eq. 34
        var betal,boardfactor,cablefactor,lambda;
        var zeq,zant,ztot,icm,ffmax;
        var temp1,temp2,temp3;
        for (i=0;i<vtotal.length;i++){
            lambda=c0/(x[i]*1e6);
            betal=2*pi*x[i]*1e6/c0*ltrace*Math.sqrt(epsr);  //Eq. 25
            if (lambda>=lboard*4)
                boardfactor=Math.sin(2*pi*lboard/lambda);
            else
                boardfactor=1;  //Eq. 32
            if (lambda>=lcable*4)
                cablefactor=Math.sin(2*pi*lcable/lambda);
            else
                cablefactor=1;  //Eq. 33
            zant=rmin/boardfactor/cablefactor;
            veq=vtotal[i]/Math.abs(Math.cos(betal))*z0/Math.sqrt(z0*z0+Math.pow(Math.tan(betal)*zne,2));//Eq. 26
            temp1=z0*z0*zne+zne*z0*z0*Math.pow(Math.tan(betal),2);
            temp2=Math.pow(z0,3)*Math.tan(betal)-Math.pow(zne,2)*z0*Math.tan(betal);
            temp3=z0*z0+Math.pow(zne*Math.tan(betal),2);
            zeqr=temp1/temp3; // Eq. 27
            zeqi=temp2/temp3; // Eq. 28
            ztot=Math.sqrt((zant+zeqr)*(zant+zeqr)+zeqi*zeqi);
            icm=veq/ztot;  //Eq. 35
            ffmax=findFmax(x[i]);
            y[i]=sigNumber(20*Math.log(60*icm*ffmax/r*1e6)*Math.LOG10E); //Eq. 29
        }
```