

# CONMTL Version 1.0

## User's Manual

Institut für  
Theoretische Elektrotechnik



[www.tet.tuhh.de](http://www.tet.tuhh.de)

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## 1 General Remarks

*CONMTL* enables the computation of the per-unit-length parameter matrices **L**, **C**, **G** and **R** and, based on this, the admittance matrix **Y** of a multiconductor transmission line of arbitrary cross section. The **Y** matrix can be loaded by the *CONCEPT-II* network solver *CONCIRC* (see <http://www.tet.tuhh.de/concept/network-solver>). Using this software transmission lines can be terminated by lumped elements or interconnected in an arbitrary manner.

Input:

- Geometry of cross section in an x-y coordinate system; length of transmission line
- Rel. dielectric constant, loss tangent, conductivity
- Discretization of elements in cross section
- Frequency sampling

Output:

- E-field distribution in cross section with high resolution
- Per-unit-length parameter matrices
- S-parameter matrices for usage in external programs, Touchstone format.
- S-parameters as a function of frequency at ports to be selected
- Y-parameter matrix in HDF5 format for usage in *CONCIRC*

*CONMTL* is under development at the Institut für Theoretische Elektrotechnik at the Technische Universität Hamburg (<http://www.tet.tuhh.de/>) and includes work that has been

mainly done by [1], [2] and [5].

The program is based on a 2D method of moments (MoM) technique. In a first step the equivalent surface charge distribution is computed as the solution of a system of linear equations. Then it is possible to determine the per-unit-length parameters. This data is applied for setting up the Y-parameter matrix based on multiconductor transmission line theory [3].

## 2 Theoretical Background

First the per-unit length capacitance matrix  $\mathbf{C}$  is computed by solving the following integral equation for 2D electrostatic problems:

$$\Phi(x, y) = -\frac{1}{2\pi\epsilon_0} \int_{\partial S} \sigma(x', y') \ln \sqrt{(x-x')^2 + (y-y')^2} dx' dy'$$

with  $\epsilon_0$  as the vacuum permittivity,  $\Phi(x, y)$  as the potential at point  $(x, y)$  and  $\sigma(x', y')$  as the surface charge on PEC conductors or polarization charges on dielectric boundaries (boundary element method, BEM). In general the 2D charge distributions are expanded by constant basis functions (constant charge blocks) defined over straight segments which leads to a piecewise linear approximation of the cross-sectional geometry of the transmission line under consideration and a step approximation of the physical charge distribution. As boundary conditions we have the constant potential on conductors and the constant dielectric flux density along the surface of coatings or substrate.

The per-unit-length inductance matrix  $[\mathbf{L}'] = \mathbf{L}$  is found according to the following expression:

$$\mathbf{L}\mathbf{C}_0 = \mu \mathbf{I} \Leftrightarrow \mathbf{L} = \mu_0 \epsilon_0 \mathbf{C}_0^{-1}$$

with  $\mathbf{I}$  as the identity matrix and  $\mathbf{C}_0$  as the per-unit length capacitance with dielectric material not being present. Hence the capacitance matrix is computed two times, namely with and without dielectric material.

The conductance matrix  $\mathbf{G}$  is computed by means of this equation [2]:

$$\mathbf{L}\mathbf{G} = \mathbf{G}\mathbf{L} = \mu \sigma_{\text{eff}} \mathbf{I} \Leftrightarrow \mathbf{G} = \mu_0 \sigma_{\text{eff}} \mathbf{L}^{-1}.$$

The implemented technique for the computation of the resistance matrix  $\mathbf{R}$  [Ohm/m] is in principle only valid for strong skin effect. The typical cross sectional dimension of a conductor should stay large compared to the skin depth as described in [2], [4].

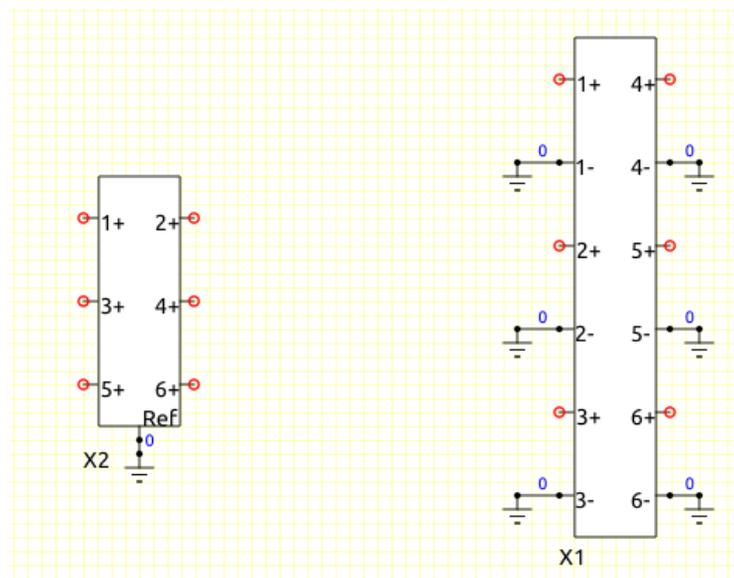
A multiconductor transmission line with  $n$  conductors is regarded as a  $2n$ -port system according to Fig. 1, here we see  $n=3$  conductors and reference conductor.

Fig. 1: Port numbering demonstrated by the example of a three-wire transmission line

Fig. 2 shows the network symbols of such a three-wire transmission line as can be selected in *CONCIRC*, which is the network solver that can be downloaded from the web

Fig. 2: Symbols of a three-wire line according to Fig. 1, see network solver *CONCIRC*.

Two alternative representations.



page of the Institute of Electromagnetic Theory (see [www.tet.tuhh.de/en/concept-2/linear-network-analysis/](http://www.tet.tuhh.de/en/concept-2/linear-network-analysis/)).

The left symbol is the standard one for a multiconductor transmission line. All conductors can be connected to network elements such as voltage generators, lumped loads or other transmission lines. The Y matrices are generated by *CONMTL* and can be loaded by *CONCIRC*. Right click on the depicted elements for this task.

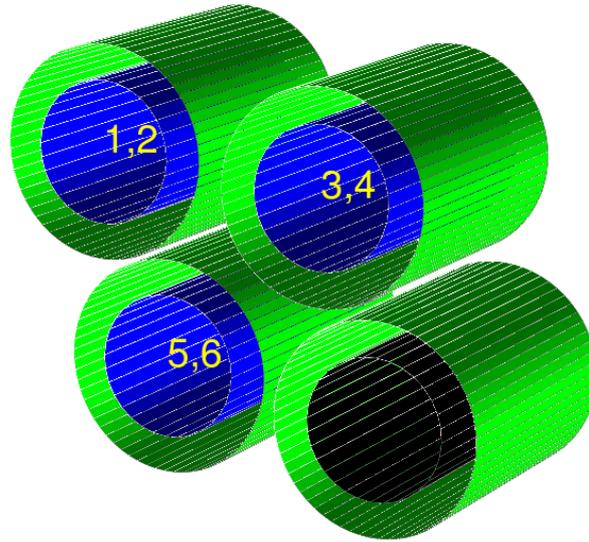


Fig. 3: Example of a three-wire transmission line. The ground or reference conductor is black, all others conductors are blue, substrate is green. The straight lines on the surfaces indicate the assumed 2D mesh, i.e. the segmentation.

For the example case the Y matrix looks like this:

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{pmatrix} = \begin{pmatrix} \underline{Y}_{11} & \underline{Y}_{12} & \underline{Y}_{13} & \dots \\ \underline{Y}_{21} & \underline{Y}_{22} & \underline{Y}_{23} & \dots \\ \underline{Y}_{31} & \underline{Y}_{32} & \underline{Y}_{33} & \dots \\ \dots & & \ddots & \\ \dots & & & \underline{Y}_{66} \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \\ U_6 \end{pmatrix} .$$

Of course, the Y matrix is frequency dependent and therefore a full 6x6 matrix will be stored for each frequency step. The Y matrix is a fully populated  $2n \times 2n$  matrix with  $n$  as the number of conductors. All complex coefficients are computed based on multiconductor transmission line (MTL) theory as described in [3].

Generally the following steps are necessary:

- 1) Computation of the Y matrix based on the per-unit-length transmission line (TL) parameters for each frequency step by *CONMTL*. An .h5 file containing all Y matrices is stored in the working directory. Frequency dependent S parameters are ready to be displayed and stored.
- 2) Computation of a network including the transmission lines with the network solver *CONCIRC*

### 3 Working with the GUI

The graphical user interface is depicted in Fig. 4. The icons of the left vertical section are indicating the basic type of transmission line that can be modified. By default conductors are blue, ground conductors are black, dielectric material is green.

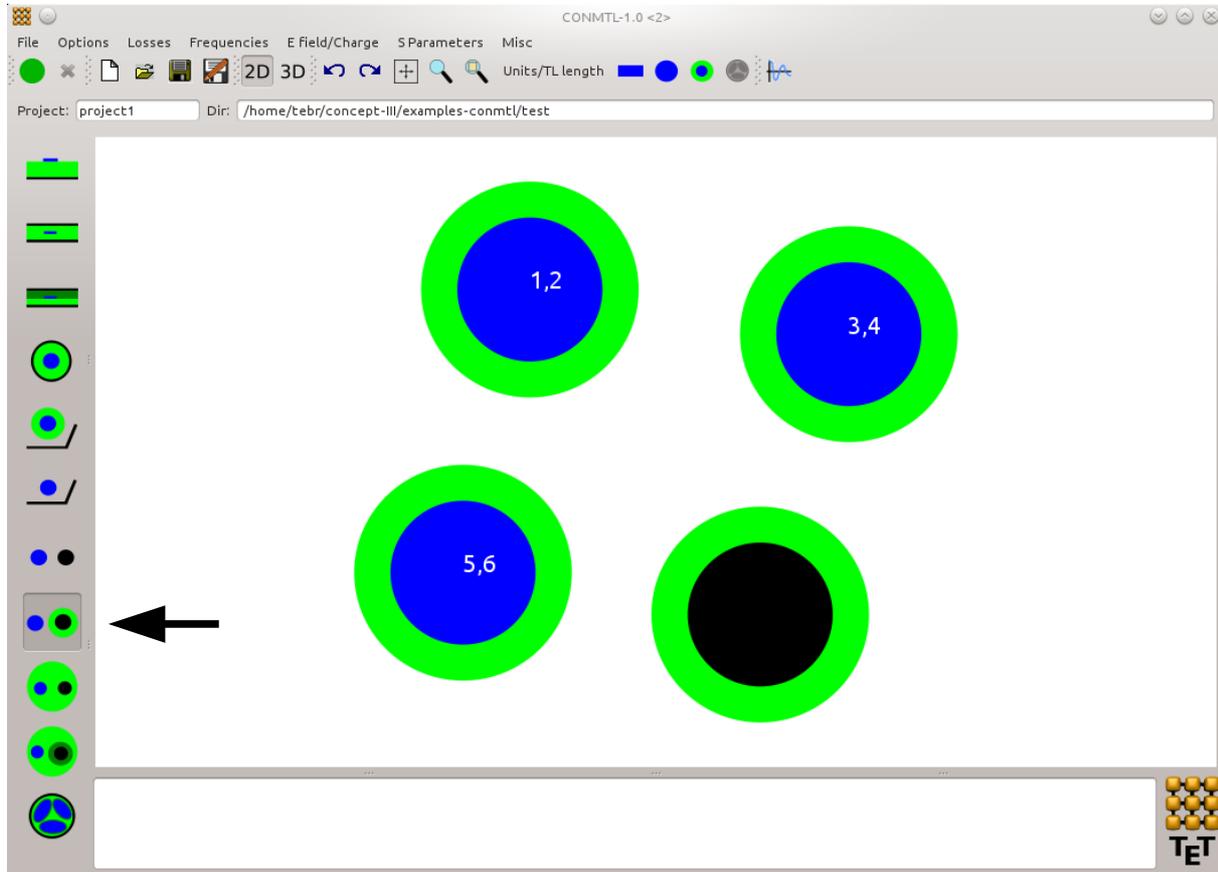


Fig. 4: The graphical user interface of CONMTL. The example structure according to Fig. 3 is shown in the display area in 2D mode. Moving the mouse pointer over an element provides information about the number of segments etc. .

For the depicted cross section the indicated TL type has been activated on the left icon bar, the blue non-coated conductor has been erased and three additional coated conductors have been added by selecting the suitable symbol in the head section and clicking into the display area.

The cross section of a transmission line has been defined in an x-y Cartesian coordinate system. Ideal ground is always positioned at  $y=0$ , if activated.

'Project': Enter here the name of the transmission line project, for example *Three-wire-line* or *Stripline* or *Coaxial-cable* or whatever is appropriate for clearly identifying the corresponding MTL structure. The name of all relevant files will start with the chosen project name.

### Basic handling

Select the appropriate predefined type of transmission line cross section in the left vertical icon bar and click into the display area → the selected configuration appears in 2D drawing mode. Now further conductors can be added by choosing one of the cross sections that are indicated in the tool bar above the display area (  ) and then clicking at the desired position of the display area.

Right click on an element provides the possibility to

- Edit the properties (change of coordinates, radii, permittivity and so on.)
- Move
- Copy or
- Delete

it.   : Undo/redo. <Ctrl>+Z: Undo

Turning the mouse wheel enables zooming in and out with reference to the current mouse pointer position.  : Choose region to zoom in by dragging the mouse. Clicking on  displays the cross section in the default position again.

Before specifying the cross section it is recommended to click on  in order to set the transmission line length (m,mm,mil) and the units for the cross sectional dimensions (mil, mm).

Example:

Right-clicking on dielectric material (color green, see Fig. 4) and selecting 'Edit properties' gives (see Fig. 5):

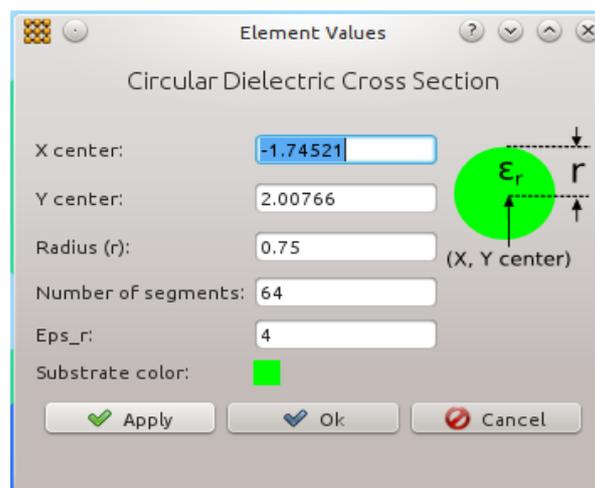


Fig. 5: Dialogue window for setting the properties of a dielectric material of circular cross section.

An important quantity is the number of segments (number of basis functions) to be specified for all elements. This number should be large enough to ensure

- a sufficient approximation of the cross sectional boundaries by straight segments
- to have a good approximation of the surface charge distribution and
- to be fine enough in case of further electrodes or substrate which might be positioned locally in very close vicinity.

Overlapping elements or elements that are too close to each other (not enough space between them in terms of the 2D grid) cause an error marked accordingly in the display area. Observe the grid by activating , turn the mouse wheel for zooming in or out.

Messages which are issued by the program can be inspected in the bar below the display area.

The meaning of all icons is indicated by tool tips that appear by mouse over.

### 3.1 The 3D view option

Pressing  provides a 3D view of a short piece of line in the display area. An example can be seen in Fig. 3. This view shows the discretization of all TL elements of the cross section. Each line segment corresponds to an unknown of the equation system to be set up and solved.

By means of  it is possible to identify coordinates and measure distances by right clicking on a pair of boundary nodes. The data is given in a window that pops up.

The position of  $y = 0$  is indicated by clicking on .

Use <Ctrl>+<Shift> + left mouse button → drag: move the whole TL cross section in the display area or use .

### 3.2 Displaying the cross-sectional E field distribution

Investigation of the local E field distribution is a powerful method for validation: of course all E field vectors have to be perpendicular on conductor boundaries. At dielectric boundaries we should have the following situation:

$$E_{n1} \epsilon_{r1} = E_{n2} \epsilon_{r2} = D_{n1} = D_{n2}, \quad E_{t1} = E_{t2} .$$

Click on . A window according to Fig. 6 pops up.

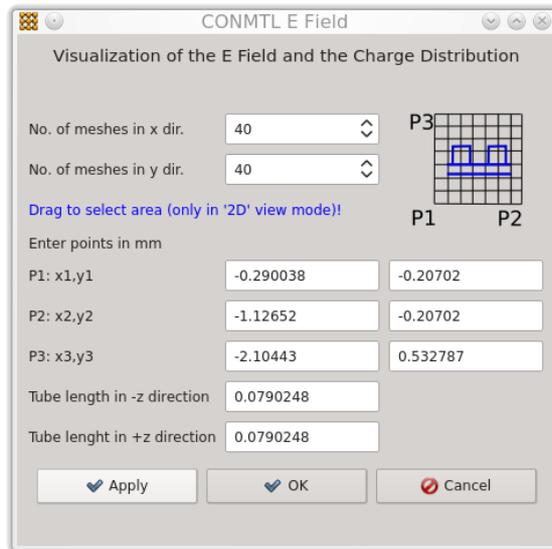


Fig. 6: Window for controlling the representation of 2D E field distributions

Now a suitable region or the overall transmission line cross section can be conveniently selected: press and hold the left mouse button and drag. Note: This is only possible in 2D mode. Immediately after clicking on **OK** (see Fig. 6) the E field distribution will be shown in 3D mode based on the chosen number of mesh steps in x and y direction. To improve the resolution of the field distribution it is not necessary to leave the 3D mode. Simply click on **E field/Charge** again and enhance the 'No. of meshes in x dir.' and / or the 'No. of meshes in y dir.' in the window according to Fig. 6 which comes up again. Then press **OK** again.

By default the potential of all conductors is set to 1V. To change this go back to the 2D mode and open the properties window of the corresponding conductor by selecting it with a right mouse click. Set the potential to the desired value. Proceed then as described above.

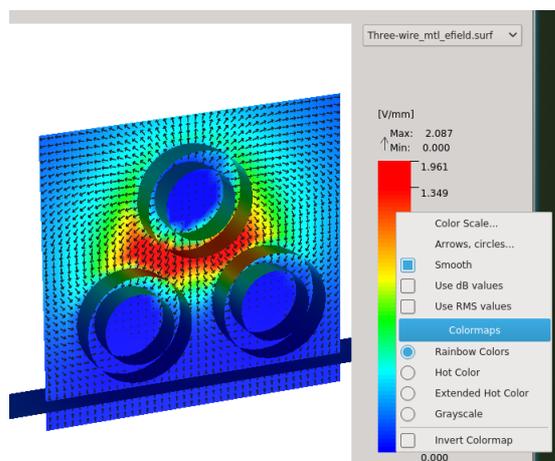


Fig. 7: Example of an E field distribution.,; three coated conductors over a finite ground plate

Scaling of the field distribution for a good representation can be done as follows: right click onto the color map on the right side of the display area. A pull-down menu opens providing a large range of features for modifying the representation. As always two files with corresponding data are loaded namely field data and charge distribution; notice the file being active!

### 3.3 Losses

The theoretical background has been outlined already in Sec. 2.

By default an unphysical high conductivity of  $100 \cdot 10^8 \text{ S/m}$  is assumed for conductors if no value has been entered under 'Conductivity of all conductors [S/m]', see Fig. 8 (here we see the conductivity of copper,  $56 \cdot 10^6 \text{ S/m}$ ). Assuming ideal conductivity would lead to difficulties in the computation of the  $\mathbf{Y}$  matrix in some cases.

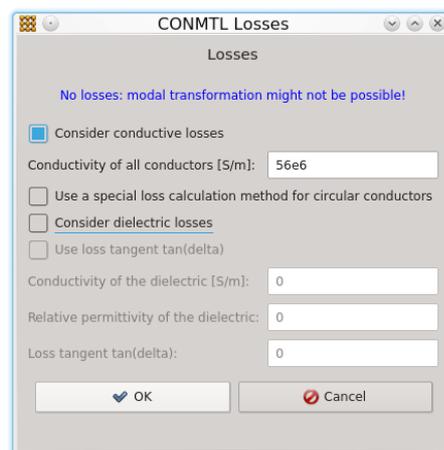


Fig. 8: Both dielectric losses and conductor losses can be considered. Dielectric losses: A homogeneous dielectric material with constant conductivity for all frequencies is assumed. Losses in conductors: Cross section should stay large compared with the skin depth!

Losses are not possible in case of an ideal ground.

### 3.4 Nonuniform transmission lines

CONMTL offers the possibility to investigate nonuniform transmission lines.

Click on **TL values** → a window as shown in Fig. 9 opens. Select **Uniform or nonuniform transmission lines (Runge-Kutta method)** as indicated. Now the Telegrapher's equations are solved numerically based on a Runge-Kutta scheme [ 1]. The method can also be applied to uniform transmission lines (only two supporting points at the beginning of the line and at the end of the line are necessary) and has proven to be a very stable algorithm. It does not suffer from the known difficulties at the modal transformation solving the Telegrapher's equation in the standard manner. Disadvantage is the higher computation time.

CONMTL TL Values

Unit TL length:

Unit cross section:

Uniform or nonuniform transmission line (Runge-Kutta method)

Cable twist No. of twists per m  Segments per twist

Coordinate points for TL:

	x [m]	y [m]	z [m]
Point 1	0	0	0.02
Point 2	0.330694	0	0.0368688
Point 3	0.661388	0	0.0803612
Point 4	0.992082	0	0.132136
Point 5	1.32278	0	0.170358
Point 6	1.65347	0	0.178909

Append  No. of points

Fig. 9: Specifying the course of a nonuniform transmission line support points  $x,y,z$  (nodes).

The course of a MTL has to be described by a series of subsequent support points or nodes; each node is given by its Cartesian coordinates  $x,y,z$ . Nodes can be loaded from ASCII files with the  $x$ ,  $y$ , and  $z$  coordinates of a node in each row.

The course of the MTL will be approximated based on the given nodes by spline interpolation.

The path of the conductors with respect to a plane at  $y=0$  (local coordinate system) will be displayed by clicking on **Show resulting cable** (see Fig. 9).

Currently only variation of the conductor heights with respect to ground (finite or infinite) is possible. The mutual distance of all conductors in the MTL cross section remains unchanged along a line.

For details notice Fig. 10.

- All conductors of the MTL cross section are described in a local  $x-y$  coordinate system, see *Cross section (2D)* in Fig. 10.. Micro-strip lines and strip lines can currently not be considered as nonuniform lines (March 2020).

It has to be emphasized again that the cross sections of all conductors of an MTL refer to the local  $x-y$  origin. The origin can be indicated by **Options** → **Draw origin**. It is a good idea to specify all conductors such that the  $x-y$  origin corresponds (least approximately) to the centroid of all participating conductors.

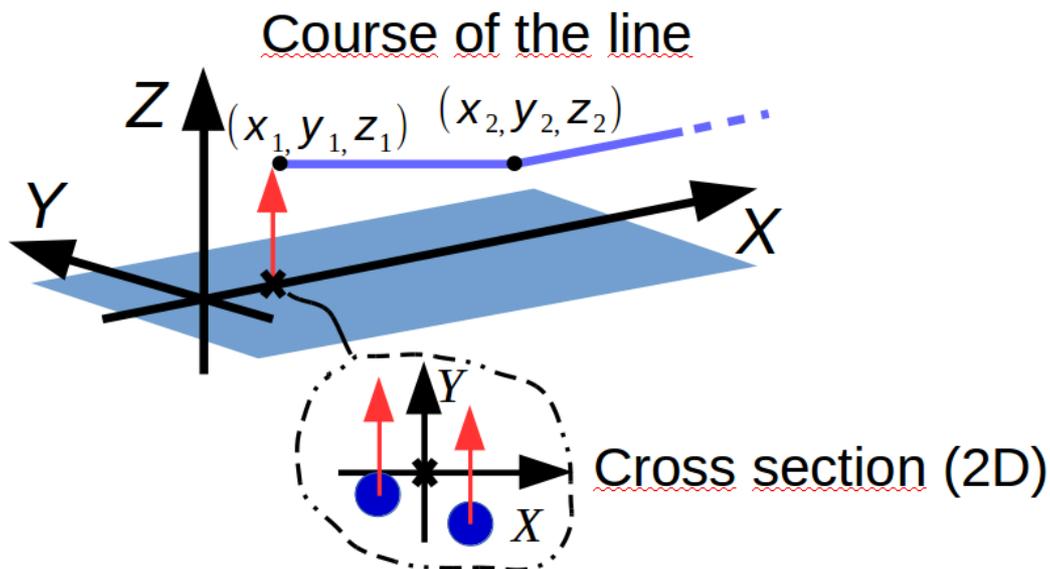


Fig. 10: Local and global coordinate system for specifying a nonuniform MTL. Different coordinate systems had to be introduced from historical reasons.

*Local x-y system (2D):* Specify the position of the conductors with respect to the local origin marked by a cross.

*Global x-y-z system:* Specify the course of the line. The z coordinates of the nodes determine the local height of the line. **The projection onto the x-y plane determines the effective length of the MTL as considered in the computation.** The physical length of the conductors is somewhat larger in general.

- In contrast, the course (the path) of the MTL has to be specified in a different, global x-y-z coordinate system. This is accomplished by entering a series of support points (nodes) describing the course of the center line as also illustrated in Fig. 10..

Important to note is that the z coordinates of the nodes determine the local height shifts of all MTL conductors with circular cross section (also ground wires). The final height of a conductor axis is given by the sum of its z coordinates (global) and y coordinates (local).

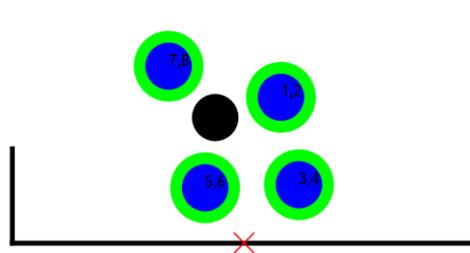
Ideal ground and finite straight ground conductors are not affected by z coordinate changes. All finite elements of a cross section are shifted in position according to  $(x_1, y_1), (x_2, y_2), \dots$ .

Examples:

The center of a conductor is at  $y = 0 \text{ mm}$  (local coordinate system) and  $z_1 = 0.02 \text{ m}$  (global coordinate system) → the center of the conductor is at  $z = 2 \text{ cm}$ .

The center of a conductor is at  $y = -5 \text{ mm}$   $y = -5 \text{ mm}$  and  $z_2 = 0.03 \text{ m}$  → the center of the conductor is shifted to  $z_2 = 2.5 \text{ cm}$  in the global coordinate system.

The user has to ensure that all conductors of the MTL stay above the reference conductor which may be an ideal ground plane (always  $y=0$ ) or a finite ground, that may be formed by one or more straight black lines as demonstrated in the following figure:



*Fig. 11: Four coated wires and a ground wire in a finite trough described by three straight lines. The ground wire changes its height with respect to the horizontal line just as the coated conductors do. The distance of all round wires to the side walls remains constant in case of a non-twisted MTL.*

***In case of a twisted MTL the user has to pay special attention that no conductor with circular cross section gets too close to the grounded walls. The twist goes around the origin of the local x-y coordinate system. The cross in the middle of the bottom wall marks the origin of the example cross section. Hence a conductor twist would make no sense here...***

- The minimum number of nodes is two. If these nodes have the same  $z$  coordinates, a uniform MTL is described.

Based on the sequence of nodes a piece wise linear approximation of the MTL is given, a “smoothing” by means of spline functions will be automatically carried out by the program.

- **The effective length of the MTL under investigation solely corresponds to the projection of the center line onto the x-y plane.**
- A MTL should run “more or less” parallel to the x-y plane, i.e. a very “strong” variation in height between adjacent nodes should be avoided.
- “Ground” is not restricted to an ideal ground but can be described by one or more finite black lines, see for example the four-wire MTL cross section in Fig. 11. as derived from the basic type . Important to note is that round ground conductors (●) change their height as all wires do. The other ground conductors (“straight

black lines” ) do not change their vertical position.

- The conductors of the MTL may be twisted clockwise or counterclockwise: Enable **Cable twist** and enter the number of twists per m and the of number segments (rotated cross section) per twist.
- Field excitation not yet possible (March 2020)
- Plotting of the field distribution is possible but is restricted to the resulting overall cross section as given by the first node.
- S-parameters are available and the Y matrices can be loaded by *CONCIRC* (network solver) for further treatment as in the case of uniform MTLs.

### 3.4.1 Basic example of a nonuniform TL

See example directory, folder *Nonuniform-Single-Wire*.

A single wire line over an ideal ground is treated. The course of the conductor center is given by:

$$F(x) = (0.1 - 0.08 \cdot \cos(2 \cdot x)), \quad x = 0, \dots, 2 \cdot \pi$$

Overall length: 6.28 m. The line is described by 20 support points.

Minimum height: 2 cm, maximum height: 18 cm. Conductor radius: 1 mm. The frequency steps are in *mtlfreq.in* (specify under **Frequencies**).

The conductor cross section is specified according to Fig. 12 .

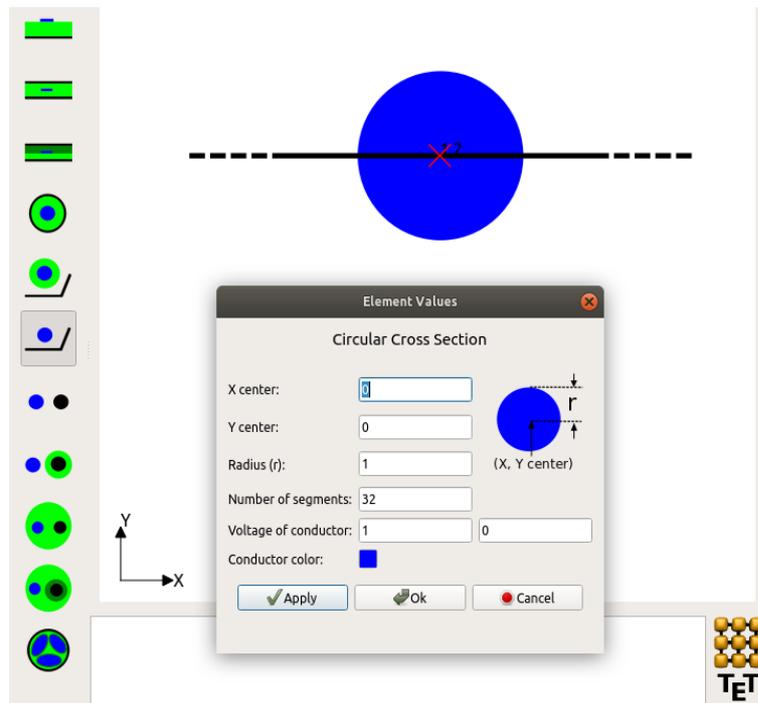


Fig. 12: Non coated wire with its center positioned at  $x=0, y=0$ . The course of the conductor is given by 20 nodes (click on **TL values** for the node coordinates). The local height of the line is solely determined by the  $z$  coordinates of nodes.

The center of the wire cross section (color blue) is in the origin of the local  $x$ - $y$  coordinate system. The physical height of the line corresponds to the  $z$  values of the nodes which describe the path of the line (click on **TL values**).

Running *CONMTL*, a wire file is automatically generated, here *Nonuniform\_mtl\_cable.wire* (in general: *project\_name\_mtl\_cable.wire*). Such a file can be loaded into *CONCEPT-II* for validation purposes, notice Fig. 13 for the TL under investigation. At the beginning and at the end ports are defined for a MoM-based reference computation, see subfolder *MoM*.

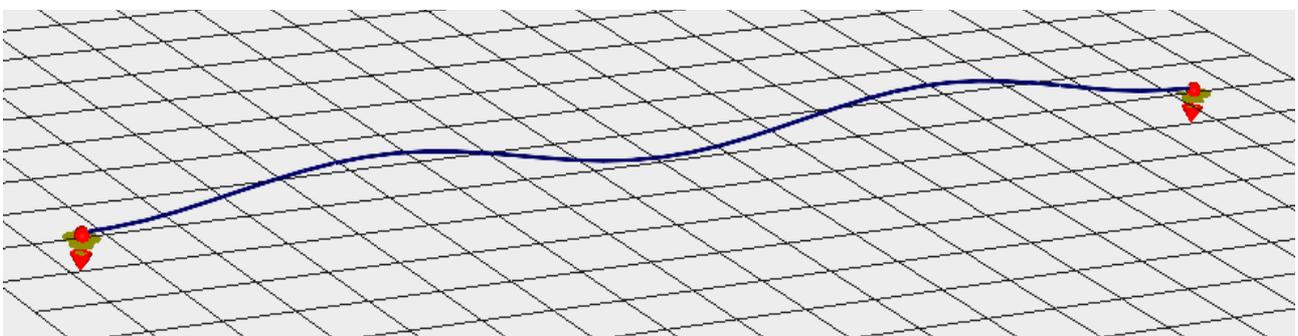


Fig. 13: The considered TL over an ideal ground plane. Picture from *CONCEPT-II*. A wire file is automatically generated by *CONMTL*.

The computed results for  $S_{21}$  are demonstrated in Fig. 14. As can be seen there is a slightly growing deviation between the curves with increasing frequency. There are two reasons for this:

- In MoM the true length of the line is considered. In addition two vertical sections had to be introduced (connections to the ground), which are enhancing the overall conductor length and are not considered in the MTL computation. Hence the peaks of the red curve are a little bit shifted to the left.
- In the MTL computation an ideal lossless line is considered whereas in the MoM computation radiation loss cannot be avoided leading to a slight lowering of the resonance peaks with increasing frequency.

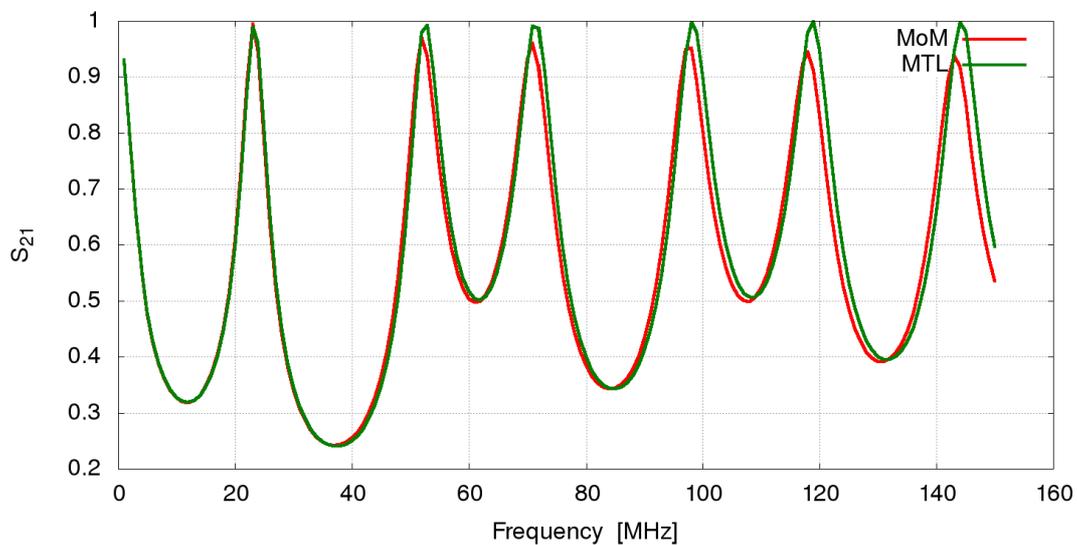


Fig. 14: The  $S$  parameter  $S_{21}$  computed by the MoM-based full-wave solver *CONCEPT-II* (red curve) and *CONMTL* (green curve)

A more advanced example can be found in the folder *Nonuniform-MTL-Network*.

Overall nonuniform MTL network: *MTL-concept-II.png*

The equivalent circuit as drawn in *CONCIRC* (network solver): *MTL-concinc.png*

The computed results: *MTL-MOM-Reference.png*

Twisted MTL section: *3C-twist\_mtl.mtl* (3 conductors)

“Sinusoidal” two wire line: *2C-wave\_mtl.mtl* (2 conductors)

Single wire line: *1C-straight\_mtl.mtl* (1 conductor)

Frequency steps: *mtlfreq.in*

Control file for *CONCIRC*: *Connected-transmission-lines\_network.cir*

Folder *mom-reference*: fullwave MoM-based validation (*CONCEPT-II*)

Procedure:

Load the .mtl files successively and run the *CONMTL* simulation each time, then start *CONCIRC* and select “Prsrc1” and “PrA1” for presentation. The MoM-based computation takes a much longer time.

### 3.5 Field plots as a function of time

In some cases it may be helpful to observe how the E field distribution in the MTL cross section behaves when the phases of the conductor voltages successively change from 0° to 360°. For the desired purpose a sufficient number of steps has to be selected (16 steps are a good choice). Repeating the series of pictures again and again provides a movie. This may be of special interest for three-phase systems (or similar) - the rotating E field is displayed (set the phase of the conductor voltages to 0°, 120° and 240° for example).

1. Right click on the conductor symbol → **Edit properties** → specify voltage and phase
2. Click **E field/Charge** → Enter the number of phase intervals (16) → select a 2D window by dragging the mouse pointer (make sure that the number of meshes is appropriate) → **OK**
3. The E field distribution is displayed for the initial phase → **Animate** → (a movie is displayed, eventually lower the presentation speed) → eventually scale the vectors and colors by right clicking on the right color widget.... Note that both the surface charges and the E field are displayed. When scaling the representation make sure that the right data is active (*projectname\_mtl\_charge.surf* or *projectname\_mtl\_efield.surf*, respectively)

### 3.6 Frequency sampling and S parameters

As has already been outlined in Sec. 2 “Theoretical Background“ a complex admittance matrix  $\mathbf{Y}$  is computed for each chosen frequency step. Computation starts when clicking on . The frequency sampling has to be specified by clicking on **Frequencies**. A window according to Fig. 15 opens:

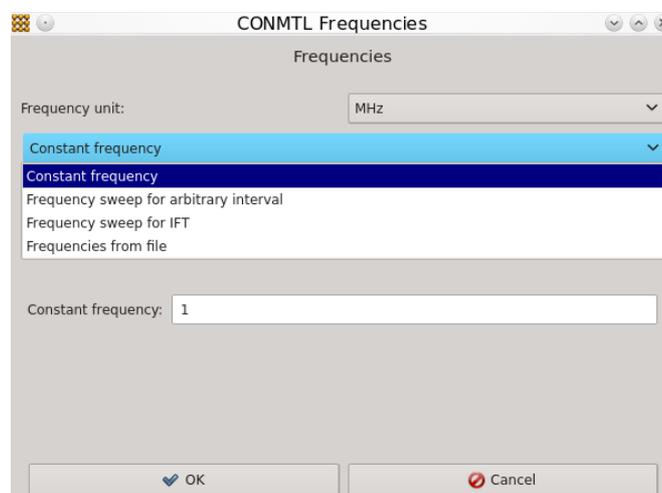


Fig. 15: Various options for the frequency sampling

Important for a proper sampling is that transmission line resonances are sufficiently covered, i.e. the peaks of resonances should be properly caught when the line is terminated by a lumped resistive load. Special requirements exist in case of an inverse Fourier transform (IFT) which can be carried out using the network solver *CONCIRC*. As has been mentioned this program is also available at the web page of the Institut für Theoretische Elektrotechnik ([www.tet.tuhh.de/concept/network-solver](http://www.tet.tuhh.de/concept/network-solver)). Practical hints for a proper frequency sampling scheme can be found in the *CONCEPT-II* manual (download PDF file from here: <http://www.tet.tuhh.de/concept/demo-version>, see Sec. 3.7.2 “Key points for performing an IFT”). An example of a time-domain analysis is given in Section 25.5 .

The computed S-parameters can be displayed by clicking on **S parameter** (gnuplot is invoked: see <http://www.gnuplot.info>, This software is not part of *CONMTL*). As illustrated in Fig. 16 S-parameters can be plotted and stored in Touchstone (2.0) format and ASCII format (see header of file for data arrangement).

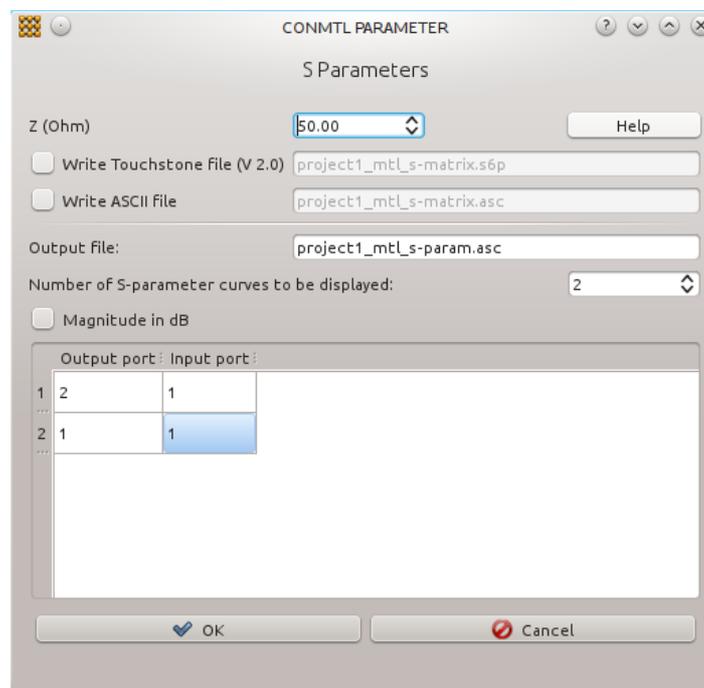


Fig. 16: Window for selection of the S-parameters to be displayed as a function of frequency

By means of the gnuplot front end which starts by clicking on the button  pictures of the curves can be created that are appropriate for further usage in presentations for example.

### 3.7 Arbitrary cross sections

In case of more complicated cross sections as considered up to here, each dielectric or conductor boundary has to be described by a series of nodes, the coordinates of which are taken from ASCII files. A boundary is described by a sequence of spatial nodes (2D, pairs of x,y coordinates) leading to a piecewise linear curve approximation. The general proceeding shall be described by an example, see example directory, folder *Power-cable*.

The format of such a boundary file is as follows:

$x_1 y_1$  first line

$x_2 y_2$  second line

$x_3 y_3$  third line

....

$x_k y_k$  last line  $k$ , boundary consists of  $k$  nodes. If the  $x,y$  coordinates of the last node correspond to the ones of the first line, the boundary is assumed to be closed.

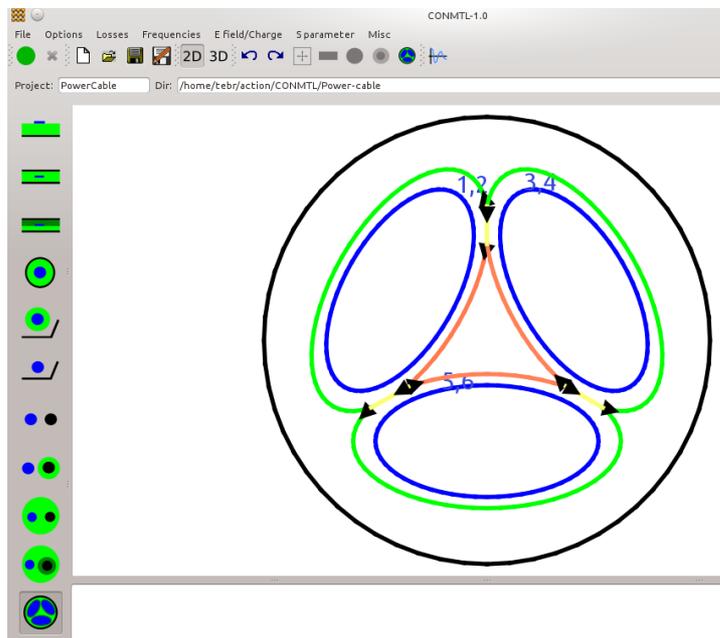
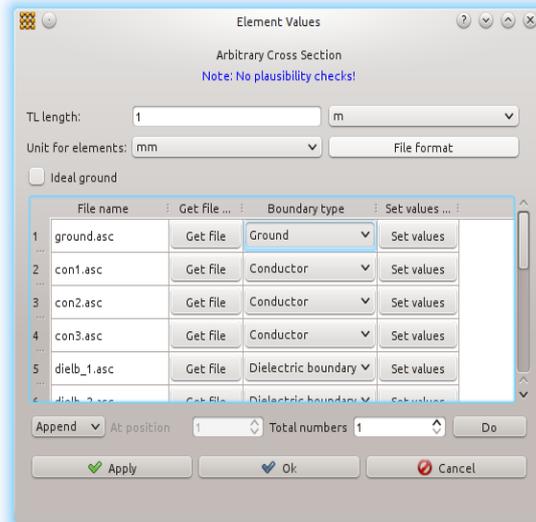


Fig. 17: A three-wire line in a common ground tube with circular cross section. The example is similar to the one described in [6].

Clicking on  in the left vertical icon bar causes the window according to Fig. 17 to open. Boundary files can be loaded (**Get file**) and specified with regard to the **Boundary type**, see Fig. 18 .

Three boundary types are available, namely **Ground**, **Conductor** and **Dielectric boundary**.

Clicking on **Set values** opens the corresponding context window where to specify the *Number of segments*, the rel. permittivity  $Eps_r$  of the medium where an electrode is immersed into, the *boundary color* etc. .



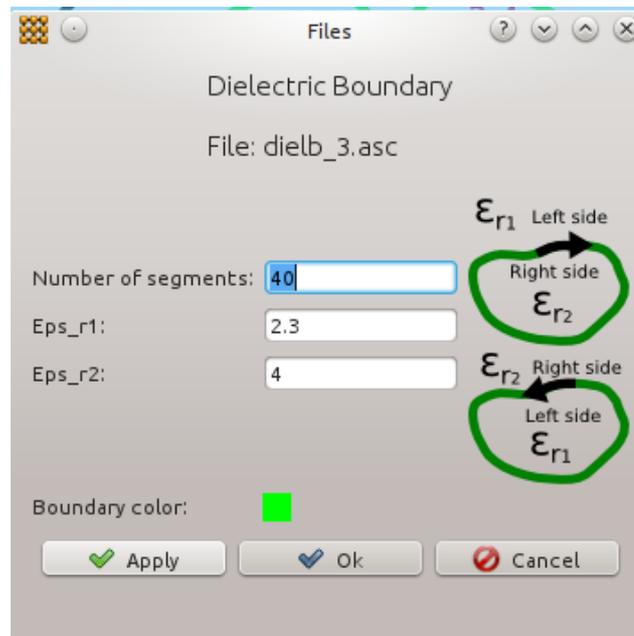
Display area:

Right

clicking on

a boundary provides the **Edit properties** and **Delete** option. **Edit properties** opens a window according to Fig. 19. The sequence of points describing the boundary is indicated by an arrow. Now the values of the relative permittivities on the left-hand side and on the right-hand side have to be entered. This is clarified by means of small pictures shown in the context window. **The user should carefully select the data as validity checks are not carried out.**

*Fig. 18: All boundaries are described by the contents of various ASCII files*



*Fig. 19: Necessary data for specifying the boundary between the conductor coating and the dielectric material inside ground tube*

Additional boundary files can be inserted activating  in the top section of the main window.

If a 'Number of segments' (see Fig. 19) is entered which is larger than the number of lines (nodes) in the corresponding boundary file, the program tries to refine the boundary description based on linear interpolation. A lower number as taken from the input file cannot be entered.

## 4 Files

### ***Project1\_mtl.mtl:***

See input field "Project" ( Fig. 16). The default name of the input control file (ASCII format). The default notation *project1* can be changed to an arbitrary name without blanks.

### ***Project1\_mtl\_y.mat.h5:***

Default name of the output file (binary file, HDF5 format). Data can be read by network solver *CONCIRC*. Contains the Y matrices of all frequency steps of the transmission under consideration.

### ***Project1\_mtl\_cappul.asc:***

Per-unit-length capacitances [pF/m], ASCII data. Format of file:

1		Always 1, first line
n		No. of conductors
C0'_11 C0'_12 ... C0'_1n	}	Matrix $\mathbf{C}_0 = [C_0']$ , <b>no</b> dielectric material present
...		
C0'_n1 C0'_n2 ... C0'_nn		
n		
C'_11 C'_12 ... C'_1n	}	Matrix $\mathbf{C} = [C']$ , <b>including</b> dielectric material
...		
C'_n1 C'_n2 ... C'_nn		

### ***Project1\_mtl\_indpul.asc:***

Per-unit-length inductances, [  $\mu\text{H}/\text{m}$  ]

n		No. of conductors
L'_11 L'_12 ... L'_1n	}	Matrix $\mathbf{L} = [L']$
...		
L'_n1 L'_n2 ... L'_nn		

On request (see menu bar, **S parameter**):

***Project1\_mtl\_s-matrix.asc:***

The admittance parameter matrix **Y** of the MTL is converted into the equivalent S-parameter matrix. ASCII data. Format: see header of file.

***Project1\_mtl\_s-matrix.snp:***

S parameter matrix of the MTL in Touchstone format (version 2.0)

***Project1\_mtl\_s-param.asc:***

S-parameters at ports as a function of frequency; notice header of file for the format. Ready for gnuplot usage. Use the *CONCEPT-II* gnuplot front end, click on **ts**. Create a png graphics file with proper axis assignment, curve color and thickness, character size, etc..

***Project1\_mtl\_tl\_param.asc:***

Single line:

Contains L', C', Z (without considering losses, Z: characteristic impedance of the transmission line)

*Two conductor transmission line:*

C'\_even, C'\_odd, Z\_even, Z'\_odd, Z\_common, Z\_diff, v\_even, v\_odd (losses are not considered yet)

$$Z_{even} = \sqrt{\left(\frac{L'_{11} + L'_{12}}{C'_{11} + C'_{12}}\right)}$$

$$Z_{odd} = \sqrt{\left(\frac{L'_{11} - L'_{12}}{C'_{11} - C'_{12}}\right)}$$

$$Z_{comm} = Z_{even} / 2, \quad Z_{diff} = 2 \cdot Z_{odd}$$

## 5 Examples

The following examples demonstrate how to apply *CONMTL*.

### 5.1 Coaxial cable

See example directory, folder *Coaxial-cable*. Start *CONMTL* and load the predefined control data.

To set up the data from scratch proceed as follows. Start *conmtl*.

1. Enter the 'Project' name: RG-213. The per-unit-length parameters of this well-known coaxial cable shall be computed numerically.
2. Click on 
3. Right-click into region with dielectric material → **Edit properties**
4. Enter  $\epsilon_r=2.3$  , 'Number of segments' : 32 → this number of segments is assumed for the outer circular ground conductor. 'Radius': 7.3 mm
5. Right click somewhere on the center conductor → **Edit properties**
6. Enter 'Number of segments' : 32, 'Voltage of conductor:' 1V, 'Radius (r)' : 2.06 mm.
7. Select **Frequencies** (menu bar) and choose 1 kHz (the value does not really matter here).
8. Press the start button: 
9. Misc → Edit → select *RG-231\_mtl\_cabpul.asc*. From this file we can take the per-unit-length capacitance as  $C'=101.148863$  pF/m.

According to the following equation we get an analytical value of

$$C' = \frac{2\pi\epsilon_r\epsilon_0}{\ln\left(\frac{D}{d}\right)} = \frac{2\pi \cdot 2.3 \cdot 8.85419}{\ln\left(\frac{2 \cdot 7.3}{2 \cdot 2.06}\right)} \text{ pF/m} = 101.13657 \text{ pF/m}$$

For the per-unit-length inductance we have

$$L' = \frac{\mu_0}{2\pi} \ln\left(\frac{D}{d}\right) = \frac{0.4 \cdot \pi}{2\pi} \cdot \ln\left(\frac{2 \cdot 7.3}{2 \cdot 2.06}\right) = 0.253034 \mu\text{H/m}$$

The value which can be taken from the file *RG-231\_mtl\_indpul.asc* is  $L' = 0.253003$   $\mu\text{H/m}$  .

Computing the characteristic impedance gives

$$Z = \sqrt{\left(\frac{L'}{C'}\right)} = 50,016 \Omega$$

The example has been chosen according to [6].

Problem left to the reader:

Change the discretization of the boundaries towards lower numbers, consider a certain frequency interval with an appropriate sampling and compute the network parameter matrices which are stored in *RG-213\_mtl\_ymat.h5*. Assume a line length of 1 m and use *CON-CIRC* to set up an equivalent circuit by assuming a voltage generator at the beginning and a terminating resistor of 50 Ohm. Introduce losses and compute again.

## 5.2 Striplines

See example directory, folder *Striplines*. Control file: *MTL-with-Loss-mil\_mtl.mtl* .

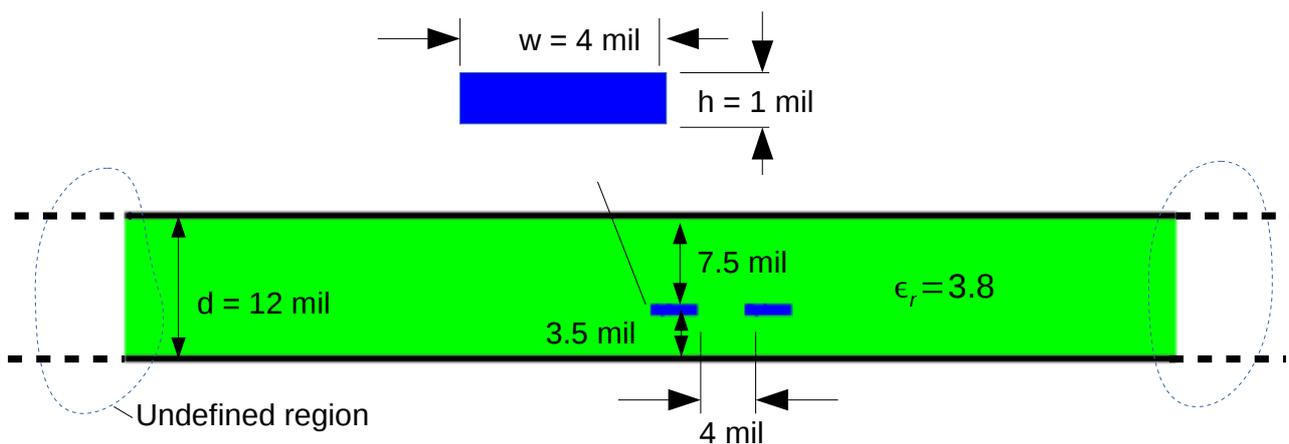


Fig. 20: Two striplines close to each other. The length of the line section is 1 Inch (25.4 mm). Conductivity of all conductors including the reference planes:  $57.0e6 \text{ S/m}$  (copper). Loss tangent of substrate  $\tan \delta = 0.03$ .

Click on **Units/ TL length** and set the TL length to 25.4 mm and set the 'Unit for cross sections' to mil. 'The structure according to Fig. 20 is entered by first selecting  from the column of icons on the left side of the display area, then click into the the display area.

1. Right click on substrate → **(Edit properties of substrate)**
2. Set 'Height (h)' to 12 → the 'Width (w)' is automatically set to 96 (eight times the height). Striplines and microstrip lines should always be sufficiently far away from the left and right boundaries, see regions marked by dotted lines in Fig. 20. At these locations the field caused by sources on the striplines should already be negligibly small.
3. Set 'Eps\_r' to 3.8 and 'Segments, top and bottom ground' to 50 and the 'TL length' to 25.4 mm.

Note that the ground plates are completely immersed in substrate. This does not matter as -provided a good segmentation- no fields (numerically zero!) will be caused by charges on the striplines as the vertical substrate boundaries are far away.

4. Right click onto the center stripline → **Move** → grasp the stripline symbol and move approximately to intended position between the plate → right click again for precise positioning → **Edit properties** → set 'X start' to 40 and 'Y start' to 3.5, → set 'Height (h)' to 1 and 'Width (w)' to 4, → set 'Grid compression (all striplines)' to 1 and 'Number of segments' to 4.

This means that we will have an adaptive grid of 4 segments on the left vertical side of the stripline; the rest of the circumference is discretized automatically in an optimized manner. Note that the voltage of the conductor is set to 1 V (necessary for displaying the field distribution, see Fig. 23). Click **OK**.

5. Right click on the just configured stripline cross section → **Copy** and position approximately → Right click on the new symbol and set precise location according to the dimensions in Fig. 20 .

6. Specify the losses. Click on **Losses** and enter the data according to Fig. 21 .

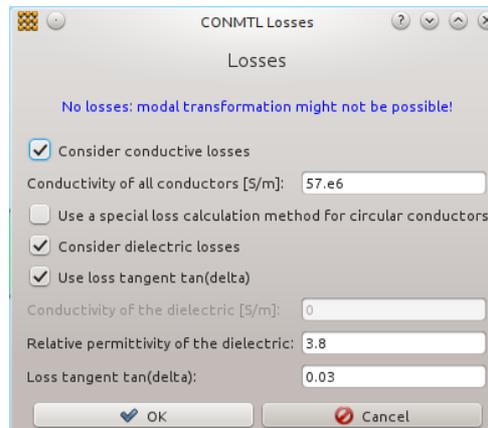


Fig. 21: Both dielectric and conductor losses are specified.

7. Specify the frequency sampling. Click on **Frequencies** . Select 'Frequency Unit' → GHz,  
'Minimum value' → 0.1, 'Maximum value' → 20, 'Interval type' → **By number of values** ,  
'Number of frequencies' → 200, click on **Generate list**, click on **OK**.
8. Start the computation by clicking on  → Note the message **Program finished, results are in MTL-with-Loss-mil\_mtl\_yamat.h5**
9. Click on **S parameter** . Set 'Number of S-parameter curves to be displayed' → 1, select 'Output port' → 2, 'Input port' → 1. The parameter  $S_{21}$  is displayed as a function of frequency (file name: *MTL-with-Loss-mil\_mtl\_s-param.asc*)
10. Make a nice figure by clicking on  → the gnuplot front end opens. The result is shown in Fig. 22 (png format). The curve is in very good agreement with the one presented in [4]. Here the same structure has been computed with a commercial FEM 3D solver, providing quite the same result, but in a much longer computation time.

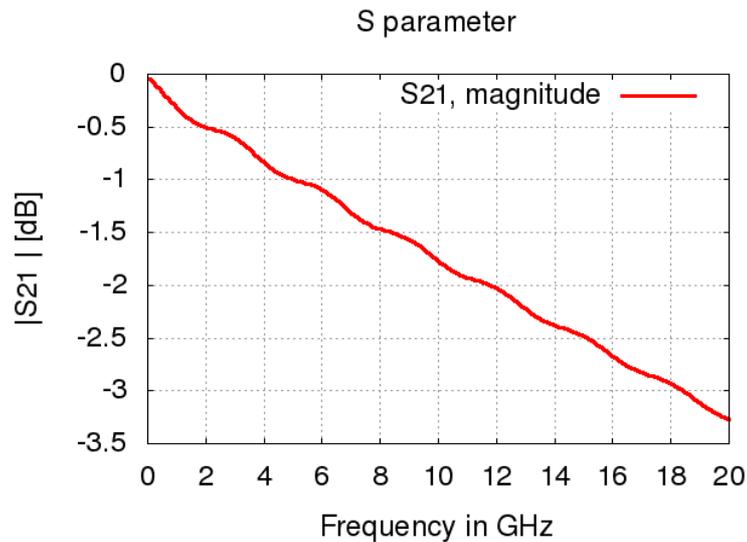


Fig. 22: Computed transmission  $S_{21}$  for the stripline example. Dielectric and conductor losses are considered. Vertical axis in dB → enter  $(\$1):(20.*\log_{10}(\$4))$  under 'Using' (gnuplot front end), **Settings** → 'Font size' 18.

11. Click on **E Field/Charge** . Drag and select a suitable area in 2D mode. Create a figure as shown in Fig. 23.

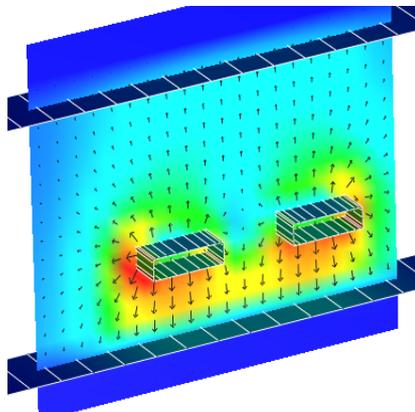


Fig. 23:  $E$  field distribution in the cross section of the stripline, both conductors at 1 V. Validation: The field strength under the lines approximately corresponds to  $E=1V/$  (height of stripline), the field vectors are perpendicular to conductors, no field outside the top and bottom plates. Notice the segmentation of the striplines, optimized mesh.

### 5.3 Multiconductor transmission line

In this example three sections of multiconductor transmission lines are interconnected as shown in Fig. 24, each section of 3 m length. The x-directed sections are three-wire lines and a return conductor. In addition there is a branch in y-direction where we have a two-

wire line and a return conductor. The radius of all non-terminating conductors is 1 mm and the mutual axial distance is 5 mm.

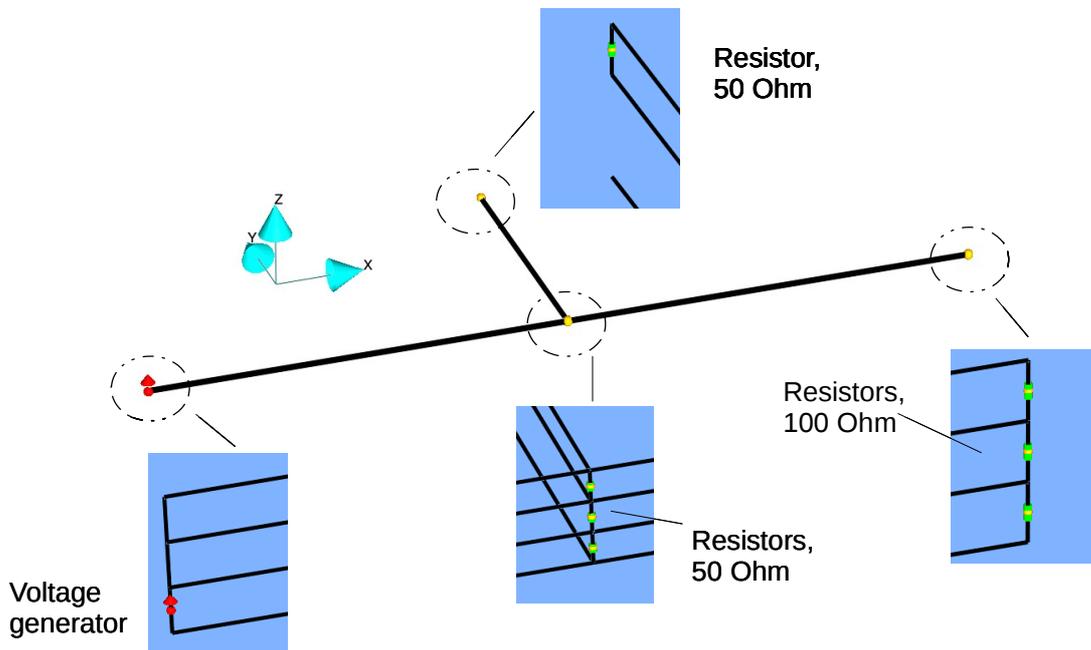


Fig. 24: A multiconductor transmission line fed at the left side by a voltage generator and loaded by 100 Ohm and 50 Ohm resistors. Validation of the voltages over the terminating 100-Ohm resistors is possible by comparing the results of transmission line and network theory with the result of a method of moments computation.

A voltage generator is placed at the left side and various resistors are located at the line ends and in the middle part where the y-directed branch is connected. The structure has the advantage that it can be computed not only by MTL but also by the method of moments as the thin-wire assumptions are fulfilled. Note that making the spacing between the conductors much smaller would cause faulty results in the MoM computation whereas it would lead to no problems in the combined method.

The MoM data is in the example directory, folder *MTL-with-branches/CONCEPT-II model*. The transmission line data is located in the folder *MTL-with-branches*.

Files: *Three-wire-Line\_mtl.mtl*, *Two-wire-line\_mtl.mtl*, *Three-wire-line\_network.cir*

First start *CONMTL* to generate the network parameter matrices (HDF5 format) then start *CONCIRC* to set up the equivalent circuit.

The equivalent circuit according to the structure as illustrated in Fig. 24 is depicted in Fig. 25. Here the transmission line sections are blocks comprising 6 and 4 ports respectively. A right click onto such a block provides the possibility of loading the corresponding HDF5 files which were computed by the *CONMTL* run, here *Three-wire-Line\_mtl\_y.mat.h5* and *Two-wire-Line\_mtl\_y.mat.h5*. For details refer to the manual of *CONCIRC*.



## 5.4 Power cable

This example has already been described in Sec. 3.7 .

## 5.5 Microstrip lines (time domain)

See example directory, folder *Microstrip\_transient*. *CONMTL* control file: *Microstrips\_mtl.mtl*.

According to Fig. 27 we have two microstrip lines close to each other. The length of the stripline section is 200 mm. All necessary data can be taken from the figure. The example has been set up according to a suggestion in [7].

As can be seen in Fig. 28 all line ends are terminated by 50 Ohm resistors (picture from the GUI of *CONCIRC*). The center block represents the coupled four-port transmission line. The voltage source provides a trapezoidal pulse with a rise time and a fall time of 0.25 ns. The interval with constant amplitude (2V) is assumed to be 2.5 ns. The voltages as functions of time are of interest at the beginning and at the end of the strips.

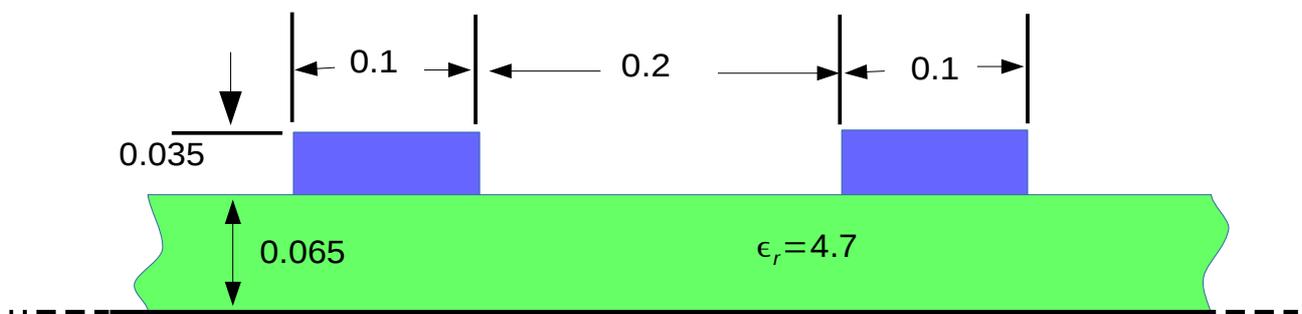


Fig. 27: Two microstrip lines on substrate and infinite ground (black horizontal line). Ideal conductivity of all metal parts is assumed.

### The *CONMTL* part of the analysis

First we have to provide the frequency domain data, i.e. the admittance matrix of the coupled transmission line which is accomplished by *CONMTL*. Most important is a proper frequency sampling. Load *Microstrips\_mtl.mtl*, then click on **Frequencies** → 'Frequency unit' MHz → **Frequency sweep for IFT (inverse Fourier transform)** → 'Basic frequency:' 5 → 'No. of frequencies:' 400. This leads to a highest frequency of 3995 MHz. The chosen sampling rate gives a smooth behavior of the S-parameters as a function of frequency including a good approximation of the quasi static values at the low frequency end (button **S Parameters**). Run *CONMTL* → The output file *Microstrips\_mtl\_ymat.h5* is generated and stored in the current working directory. Note that *Microstrips\_mtl\_ymat.h5* contains many Y-matrices according to the number of frequency steps.

### The *CONCIRC* part of the analysis

Start the network solver *CONCIRC* and load the predefined data *Microstrips\_network.cir* (see Fig. 28)

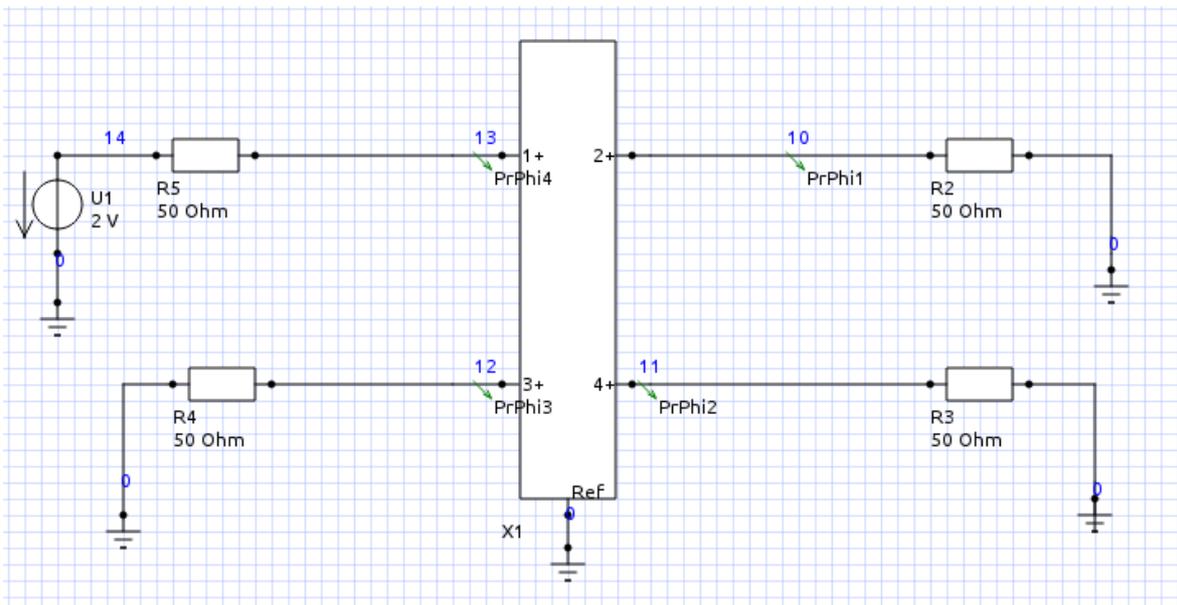


Fig. 28: The equivalent circuit of the structure under investigation. The small green arrows indicate the positions where the node voltage are computed (PrPhi1: voltage probe, potential phi 1...) The center block represents the transmission line with ports 1,2,3,4 according to the numbering shown in the display area of CONMTL.

The transmission line data have to be imported (Y-matrices provided by CONMTL):

1) Right click on the center transmission line block (created from the network symbol, see list of symbols on the left side of the CONCIRC display area) → **Edit properties** → → 'File format'

**MTL: \*.h5-file, CONCEPT-II: red\_y-mat.h5** → **Get port/MTL file...** → select *Microstrips\_mtl\_y.mat.h5* → 'Number of ports:' 4 → 'Port arrangement:' (Multiconductor) Transmission line.

For further details notice Fig. 29.

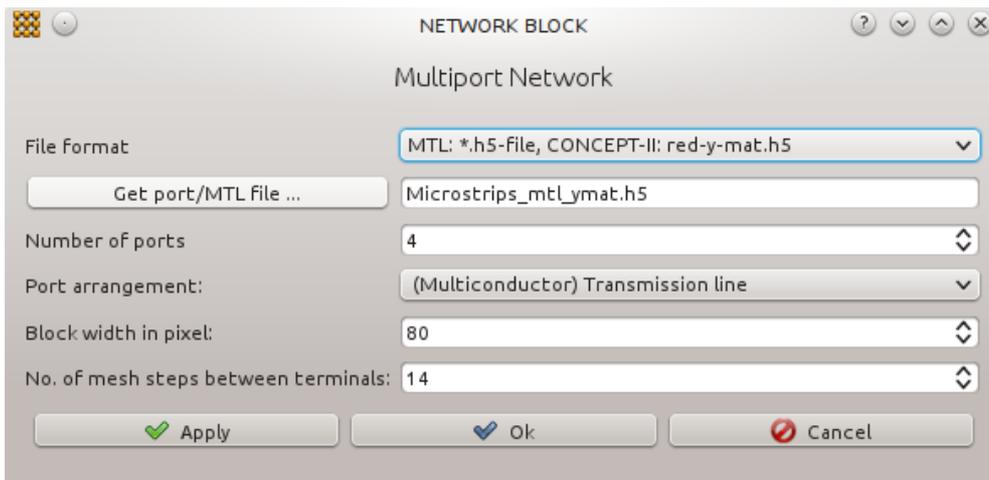


Fig. 29: Specifying the data for the MTL block

Frequency sampling: Click on **Frequencies** → specify the file *mtlfreq.in* which has been generated by *CONMTL*, see Fig. 31.

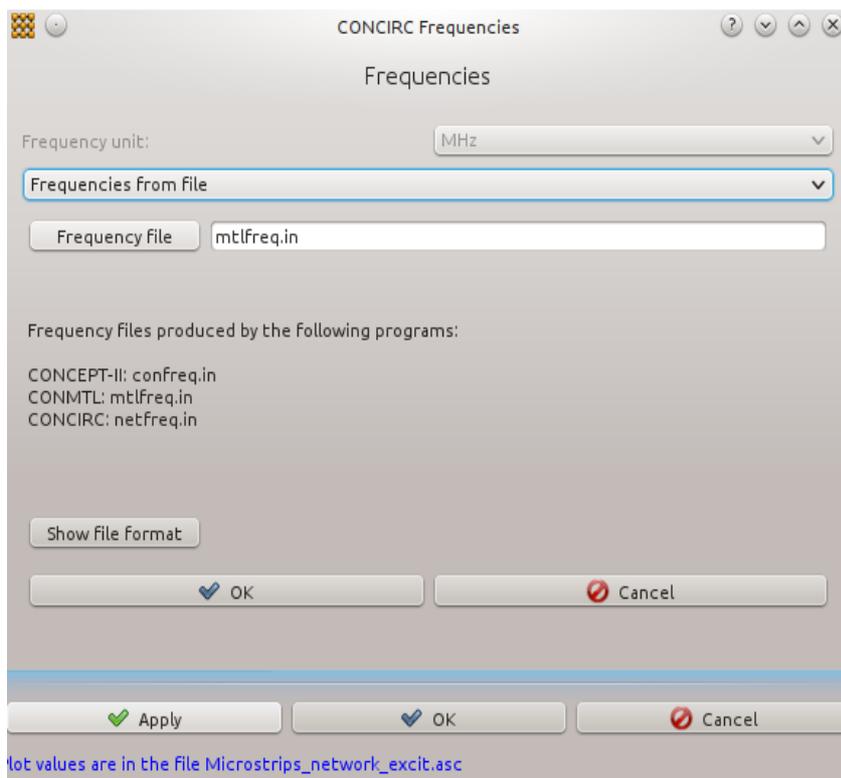
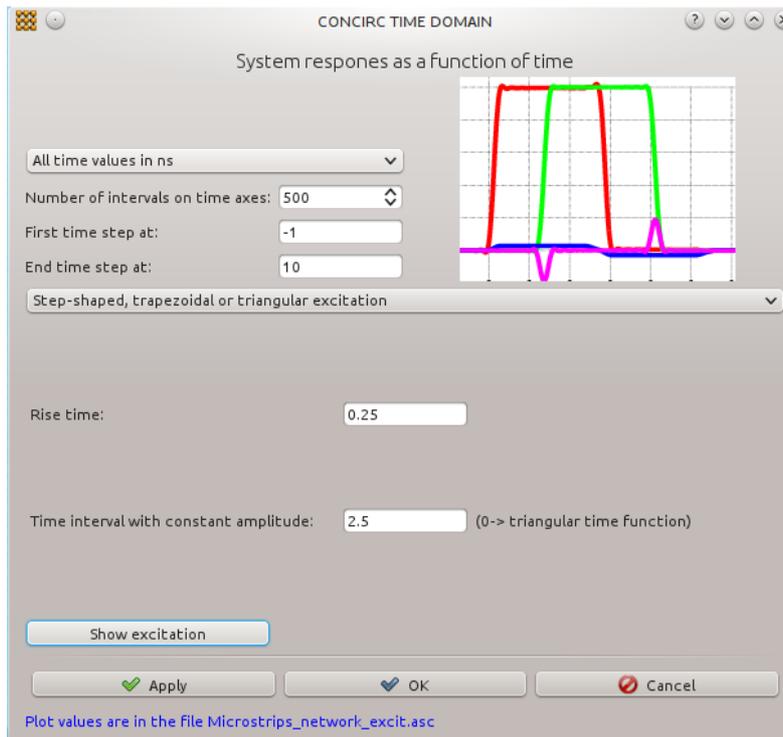


Fig. 30: In case of an inverse Fourier transform it is important to use the right frequency sampling as has been applied for setting up the corresponding Y-matrices from *CONMTL*. In our case we have to choose *mtlfreq.in*

Once all network data have been entered start the network solver by pressing the green button in the top left corner of the CONCIRC GUI. Now all system responses are computed as a function of frequency, in our case the node voltages  $PrPhi1$ , ...,  $PrPhi4$ .

The last step that remains to be done is to perform an inverse Fourier transform: **Post processing** → **Compute time domain values** . Enter the data according to Fig. 32 . Pressing **OK** leads to the final result as depicted in Fig. 33.



*Fig. 31: Specifying the time-domain function type and the time domain sampling. It is always a good idea to click on **Show excitation** first in order to make sure that the excitation function itself can be properly gained from the frequency-domain sampling.*

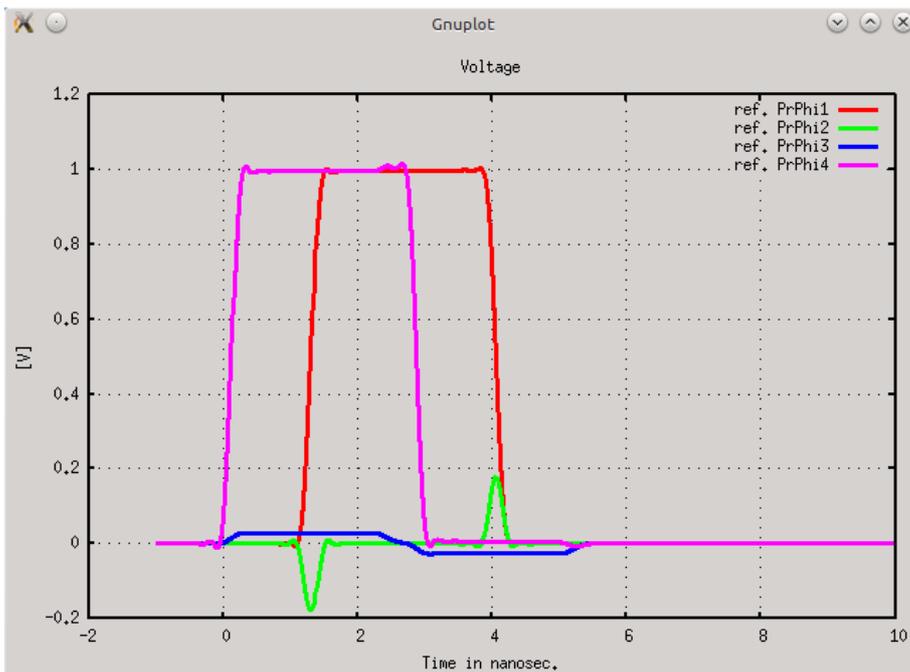


Fig. 32: Computed voltages as a function of time. The small ripples before  $t=0$  and at the end of the rising or falling slopes are unphysical (Gibbs phenomenon) and can be reduced by going to higher frequencies or to lower rise and fall times of the exciting voltage.

## 6 Licenses

CONMTL uses the following 3rd-Party packages:

Package	License	Link
OpenBlas 0.2.10 (Linux)	BSD	<a href="http://www.openblas.net/">http://www.openblas.net/</a>
Qt 4.8.6	LGPL	<a href="https://www.qt.io/download-open-source/#section-2">https://www.qt.io/download-open-source/#section-2</a>
The usage of the software is according to the GPL and the LGPL (see below)		
HDF5 1.8.12	BSD	<a href="http://www.hdfgroup.org/products/licenses.html">http://www.hdfgroup.org/products/licenses.html</a>
OpenGL , Trackball		(c) Copyright 1993, 1994, Silicon Graphics, Inc.

For details on the respective licenses/copyrights see the files in the directory

\$INSTALLATION\_DIRECTORY/licenses. Text files of the GPL and the LGPL are included (gpl.txt, lgpl.txt)

## 7 References

- [1] O. Gebele: "EMV-Analyse beliebiger Leitungen über oberflächendiskretisierten metallischen Strukturen", Diss, TUHH, 2003, VDI Verlag
- [2] S. Müller: "Including Multiconductor Transmission Lines in a Quasi-analytical Model for Multilayer Structures", Diplomarbeit, TUHH, Institut für Theoretische Elektrotechnik, Mai 2009
- [3] Clayton R. Paul. Analysis of Multiconductor Transmission Lines. John Wiley & Sons, New York, 1994
- [4] Sebastian Müller, Renato Rimolo-Donadio, Heinz-D. Brüns, Christian Schuster: "Schnelle Simulation verlustbehafteter Verbindungsstrukturen auf Leiterplatten auf der Grundlage quasianalytischer Via-Modelle und der Leitungstheorie". EMV Konferenz Düsseldorf, März 2010, Paper 69
- [5] Stanislav Skibin: "Abstrahlung von Leitungen in numerischen Modellen mit Oberflächenstromsimulation", Diss. TUHH, 2005, Shaker Verlag
- [6] S. Müller: "Korrektur und Erweiterung eines Programms zur Berechnung von Leitungsparametern auf der Grundlage der 2D-Momentenmethode mit flächigen Ladungen", Bachelorarbeit, TUHH, Institut für Theoretische Elektrotechnik, Oktober 2007
- [7] IEEE Recommended Practice for Validation of Computational Electromagnetics Computer Modeling and Simulations, IEEE Electromagnetic Compatibility Society, Feb. 2011