Accurate EM-circuit co-design of antenna systems
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Practical Antenna Design and Testing Workshop
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Agenda of the Workshop

• Loss breakdown in antenna system
  – Return loss, matching circuit losses, coupling losses, radiator and substrate losses
  – Correct setting of matching circuit optimization target

• Common error sources in antenna simulation and measurement
  – VNA calibration and reference plane
  – Matching circuit layout model
  – Matching circuit component models
  – Prototype repeatability

• Linking EM and circuit simulation for multiantenna systems

• Antenna arrays
  – Active Reflection Coefficients
  – Radiation pattern
  – Total system efficiency
Loss Breakdown in Antenna System

The perfect matching network?

After all, any antenna can be matched in $S_{11}$-sense with this circuit.
• The previous example is intentionally extreme, but an automated optimizer or trial and error-matching may very sneakily search and find such solutions
• Let us use generic lossy inductors (Q = 25 @ 1 GHz) and capacitors

What about efficiency?

Nice $S_{11}$ for Band 17
(704 – 746 MHz)!
Efficiency is not very great, -26 dB or so.

What is going on? There is seemingly nothing alarming in the matching circuit.
Loss Breakdown in Antenna System

• Any of the following can be a dominating loss factor in antenna system
  – Return loss
  – Matching component losses
  – Coupling losses to other ports in the system
  – Antenna radiator losses, expressed as radiation efficiency $\eta_{\text{eff}}$

• In the previous example, we have just a single antenna, we are assuming $\eta_{\text{eff}}=100\%$, the reflection is very small $\rightarrow$ the losses must be caused by the matching components

• A visual loss breakdown diagram greatly helps understanding the role of each of the above loss mechanisms
In this case there is no much room for speculation, as illustrated by the *Power Balance*

The loss-per-component is also available, in this case each of the three components absorbs about 1/3 of the available power.
The fundamental problem was in the optimization setup: it was set for $S_{11}$ while it should be set for the total efficiency accounting for all the loss terms.

- This setup emulates quite well the typical brute-forcing matching process, as there usually is no way to know the efficiency of the device before the chamber measurements.

For comparison, there is a solution with ~12 dB worse matching but ~24 dB higher efficiency!
Loss Breakdown Summary

- A good return loss is not guaranteed to result in an efficient antenna
- Matching component Q-values should be in par or higher than the antenna Q-value
- Port-to-port coupling can be a significant loss mechanism
- A proper optimization of the total efficiency involves many other loss terms than just return loss
Common Error Sources in Antenna Simulation and Measurement

• This part of this workshop highlights issues that influence both the simulation and the measurement
• A reliable simulation model is an extremely powerful and economical method to carry out robust designs
• Simulation vs measurement comparison is most useful when both worlds are sufficiently understood
• Design choises based on erroneous measurements and poor simulation models result in unreliable products
Reference plane location

- For a successful matching circuit design, the reference plane should be at the first matching component looking from the antenna.
- If the reference plane in the measurement differs from this location and is not compensated for, a matching circuit cannot be designed based on the measurement.
- As a rule of thumb, the reference plane should be determined with an accuracy of 1/100\textsuperscript{th} of the wavelength.
- On FR4, this translates to:
  - 1.6 mm at 1 GHz
  - 0.7 mm at 2.4 GHz
  - 0.3 mm at 5.8 GHz
Effect of errors in reference plane

Reference plane is offset by 3 mm

Wrong input impedance

Band 38 (2.58-2.62 GHz): 19 - j112 $\Omega$

True input impedance

Band 38: 203 – j362 $\Omega$
Effect of errors in reference plane

Graphs bolded at Band 38, 2.58-2.62 GHz

Matching circuit designed from wrong input data. We think it would work like this, but...

Assumed matched impedance

Realized matched impedance

Assumed original impedance

True original impedance

.. the circuit actually operates like this.
VNA Calibration

- VNA calibration and reference plane are critical, because the whole measurement is useless if the calibration has been done carelessly.
- The issue is that the conventional calibration kits set the reference plane typically on the "cable end" of an SMA connector.
VNA Calibration, de-embedding

1. Create a 2-port simulation model for the transition from the VNA calibration plane to the required plane, and de-embed computationally
   - This method is as good as the simulation model

2. Build your own calibration kit using the probes that are actually used in the measurements
   - This method is as good as your models for OPEN/SHORT/LOAD

3. Use "port extension" calibration on the VNA
   - This method is as good as your open/short are ideal and co-located on the board during calibration
   - Albeit fast, an "open probe in the air" –extension isn’t guaranteed to work even at 2.4 GHz, depending on the layout and coax to microstrip EM discontinuities
Matching Circuit Layout Model

- Let us consider a sample matching circuit with:
  1. no layout
  2. simple microstrip layout
  3. EM-simulated layout
The circuit has been designed assuming "no layout"

Simple layout and EM layout results agree reasonably well, and are both quite far away from the "no layout" result.

The shape is somewhat correct, but the impedances are rotated on the smith chart due to the non-valid reference planes at the components.
Matching Circuit Layout Model

- On these prototypes, the simple microstrip-based model was good up to ~2.3 GHz
- The EM-based layout model is very accurate even beyond this
  - The accuracy of the simple model can be improved by tuning the layout model dimensions to make simulation agree with reference measurement

No layout model at all: poor agreement with measurement
Simple layout model: good agreement with measurement
EM-layout model: excellent agreement with measurement
Matching Circuit Layout Model - Conclusions

• Matching circuit layout details influence the result in three different ways:
  1. The physical length along signal path causes impedance rotation approximately around Smith chart center – for small dimensions this is equivalent to additional series inductor
  2. The pads and traces contribute to the ground capacitance – equivalent to additional shunt capacitor
  3. Shunt component grounding to coplanar side ground may involve an equivalent small additional inductance

• Surprisingly small dimensions matter
  – Multilayer board top layers may be ~ 0.1 mm thin, and a parallel-plate capacitance value of a pad on such material is typically ~ 0.5 pF/mm²
  – As another reference, for a 0.3 mm wide CPW, the trace inductance is of the order of 0.4 nH/mm

• Layout is part of the solution, i.e., a part of the matching circuit – hence it must be modeled properly!
Matching Circuit Component Models

- One can also receive non-agreeing simulation results by using ideal component models.
- Many component vendors maintain model libraries, and lots of such libraries are available in Optenni Lab.
- The accurate component models not only provide accurate results for impedance simulation, but also allow for the voltage/current calculation as well as **efficiency optimization**.
- Using the libraries in synthesis automatically snaps results to available component values.

Beyond 2 GHz the component parasitics take over.
Matching Circuit Component Models

- **Tolerance analysis** is very important design tool that helps excluding sensitive designs at early phase, and selecting a robust design instead

Nominal performance is great, but the response is very sensitive to component tolerances!

Similar nominal performance but much more robust with respect to component tolerances! In Optenni Lab, the topology list is automatically re-sorted according to tolerance robustness!
Common Error Sources Summary

• Antenna measurement reference plane
  – Verify VNA calibration and your own soldering signature – sub 1 mm matters at 3 GHz!

• Component models
  – Accurate modeling of parasitics and component tolerances is important
  – Make use of automatic tolerance sensitivity sorting!

• PCB layout
  – Neglecting layout model may severely distort the results
  – Before building a prototype, at least a simple microstrip-based layout model should be used
Matching Circuit Design Process Summary

• Measure the antenna to be matched at the antenna input or de-embed to the location of the first matching component as seen from the antenna

• Synthesize matching circuits first with ideal components  
  – this way you find out the topology order and the best result to be expected

• Refine synthesis by using vendor library components  
  – Sort circuits by tolerance sensitivity to avoid too sensitive designs

• Sketch a simple layout model for the most promising candidates

• If you have an EM tool, create an exact EM model of the layout, and use Layout block in Optenni Lab  
  – Use Generic reactance for the components to synthesize optimal combination of L/C  
  – Again, sort circuits by tolerance sensitivity

• Build the matching circuit and measure the prototype
Linking EM and Circuit Simulation

- Optimizing an antenna system on bare circuit simulation is missing crucial EM properties, like the radiation patterns and hence efficiencies.
- However, full EM optimization of a system is extremely time consuming.
- What has to be done is grabbing a complete EM characterization of the antenna system from the EM tool in compact format, and combining it with the circuit simulation.
  - Such data consists of N-port S-parameter matrix and complex far-field radiation patterns for every antenna / frequency point.
- No knowledge is required of antenna system geometry, the element orientation or location, antenna shapes or materials.
- However, near-field quantities cannot be extracted from this data (e.g. field strength, highest surface current), but these are not usually antenna system metrics.
Linking EM and Circuit Simulation

Circuit world

EM world

\[ P_{\text{loss}} = 0.5 \times \text{Re}\{U \cdot I^*\} \]

BPF \(_7\)

\[ G = 20 \text{ dB} \]

SP4T

\[ \text{NF} = 2 \text{ dB} \]

\[ P_{\text{avail}} = 33 \text{ dBm} \]

\[ S_{nm} = b_n/a_m \]

\[ V \cdot D = \rho \]

\[ V \cdot B = 0 \]

\[ V \times E = -\frac{\partial B}{\partial t} \]

\[ V \times H = J + \frac{\partial D}{\partial t} \]

\[ E(r) = \iiint \omega \mu_0 \bar{G}(r, r') \cdot \left[ \nabla \times H(r') + \nabla \times \bar{G}(r, r') \cdot [\nabla \times E(r')] \right] \, ds' \]
Antenna Arrays

• The classical antenna array analysis is based on an analytical array factor, which essentially assumes perfect isolation between the array elements
  – The simplest array factor approximations also assume similar radiation patterns of elements, irrespective of their location in the array
  – As isolation is perfect, active reflection coefficients = reflection coefficients

• Real arrays, however, fulfil these assumptions only approximately
  – For very big arrays (thousands of elements) the assumptions are fairly well satisfied, and the array factor method is anyway more or less the only practical way to analyze such arrays

• Considering the previously discussed link between the EM and circuit simulation domains allows exact analysis of antenna arrays with any amount of coupling and with any element radiation patterns
  – We will consider the possibilities of such an exact analysis with a few examples on poorly isolated array
Antenna Arrays

- Our example is a 16-antenna linear array designed to operate at about 2 GHz

- It is already very instructive to look at the $S_{nn}$-parameters, because it is the first assessment regarding the array symmetry
  - In this case we can easily identify two groups: edge- and internal elements
Antenna Arrays

- If we look at the element-to-element coupling, we notice that the isolation is not very good, only about 10 dB or even less.

- We can conclude that the array factor approximation most likely will fail at some point, typically this occurs when the array is steered off the broadside.
Antenna Arrays

• The relevant efficiency quantity with arrays is the total system efficiency, which is defined as the ratio of radiated power from the array and the sum of available powers from the ports
  – It is worthwhile to note that total system efficiency depends upon the physical array itself, the beam direction, and the possible matching circuitry

• Let us match the antennas to WIFI band (2.4 – 2.483 GHz) with a simple two-component matching circuit using Coilcraft 0402DC inductor library and Murata GJM15 capacitor library

• The S-parameters are really good now

• However, due to finite isolation, when the array is operating, the neighboring elements feed power to each other, giving rise to active reflection coefficient
Antenna Arrays: Active Reflection Coefficients

- If both ports of a 2-port system are excited simultaneously, the wave traveling backwards at port one can be expressed as
  \[ b_1 = S_{11}a_1 + S_{12}a_2 \]
- The active reflection coefficient (ARC) of port one is defined as
  \[ ARC_1 = \frac{b_1}{a_1} = \frac{S_{11}a_1 + S_{12}a_2}{a_1} \]
  - Part of the forward traveling wave of port 2 becomes part of the backward traveling wave in port 1 and visa versa!
- If the mutual coupling term \( S_{12} \) is very small, the equation for active reflection coefficient reduces to the classical reflection coefficient
  \[ ARC_1 \approx \frac{S_{11}a_1}{a_1} = S_{11} \]
Antenna Arrays: Active Reflection Coefficients

- Let us try exciting the array with broadside excitation (uniform amplitude and phase across the element feeds)
- We observe that the ARCs have moved further away from the Smith chart center (not too seriously yet)
- For each excitation vector the ARCs will be different
- One limitation for beamforming arises from ARCs going too far away from Smith chart center, as no realizeable amplifier can drive such an array!
Antenna Arrays: Total Radiation Pattern

• The total radiation pattern looks good for broadside excitation, which is expected because the ARCs are still close to the Smith chart center.
• But if we excite the beam for endfire, the radiation pattern is far from theoretical, and the ARCs are even outside of Smith chart – the extreme consequence of inter-element coupling.

Broadside

Endfire

ARCs (broadside)

ARCs (endfire)

$S_{nn}$
Antenna Arrays: Total System Efficiency

- From the radiation patterns we see by naked eye that the endfire excitation does not radiate much power, i.e. it has poor total system efficiency.

- If we plot total system efficiency for a few array-factor based steering angles, we observe an interesting phenomenon: the efficiency drops dramatically beyond certain angle – in this case the knee point is about 55 degrees.

- The endfire efficiency is below -10 dB, as can be anticipated from the radiation pattern.
To characterize antenna array for beam steering, three interrelated quantities need to be obeyed simultaneously: radiation pattern, total system efficiency and ARCs.

- Realized beam overshoots the theoretical tilt, and the null fills at 55 degrees.
- The drop in efficiency at >60 degrees manifests itself also as intolerable spread of ARCs.
Conclusions

- One must pay attention to all loss mechanisms to make successful optimization
  - Return loss, component losses, coupling losses, antenna losses
- Common measurement and simulation error sources in antenna systems relate to measurement reference plane, layout and component models
  - Proper VNA calibration and reference plane de-embedding at the first matching component from the antenna
  - Preferably an EM-simulated model of the matching circuit layout
  - Accurate component models including tolerances
- Complete antenna array assessment requires linking of EM- and circuit worlds
  - Proper treatment of S-parameters together with radiation patterns in circuit simulation links perfectly the EM- and circuit worlds for antenna systems
  - One needs to consider total radiation pattern, total system efficiency and active reflection coefficients simultaneously
Questions?
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