Next Generation RF Design Automation Platform for Multi-antenna Assessment and Performance Optimization

Jaakko Juntunen[1], Joni Lappalainen[1] and Jussi Rahola[1]

[1]Optenni Ltd, Finland

Introduction

Along with the wireless revolution, the number of supported radio systems has increased in many portable devices, and the trend is continuing with emerging IoT and 5G applications. From a practical perspective this trend poses considerable challenges to RF designers who need to guarantee the performance of several simultaneously active radio systems while minimizing interference and power consumption.

This article elaborates on this multi-system design problem from the antenna perspective. The main trend regarding antennas is the increase of the number of antenna elements in a device, consistent with the multi-system trend referenced above, but further boosted by antenna diversity, MIMO and beamforming techniques. At the same time, the device size must not increase, so the antenna density becomes higher. This in turn leads to increased coupling, which is one of the main design challenges of a multi-antenna system. We focus on this particular problem and its consequences, but also to new methods to get the coupling problem under control.

Antenna-to-antenna coupling

As antennas are resonating structures by nature, nearby antennas tend to create mutually resonating coupled structures. The resonance is stronger if the antennas are in close proximity, and if their operating frequencies are close to each other. Similar to other physical structures, an antenna is often at resonance also at harmonic multiples of its lowest or fundamental frequency. Therefore, an antenna designed e.g. for 3GPP Band 3 (1710 - 1880 MHz) may have a strong 3rd harmonic resonance with a 5 GHz WIFI antenna (5170 - 5835 MHz). Typically, the antennas in compact devices have quite isotropic radiation patterns, and while antenna orientation can be used to exploit isolation through cross-polarization, such attempts work only in simplest cases. For example, the dipole pattern with a null radiation along the axis of the dipole allows - in best case - only three antennas to be isolated by pattern properties. Quite typically there are many more antennas than that, located in each other's near field, illustrated in Figure 1, and the industrial design does not provide the freedom to position the antennas electromagnetically in an optimal way. Therefore, one has to cope with certain amount of coupling.

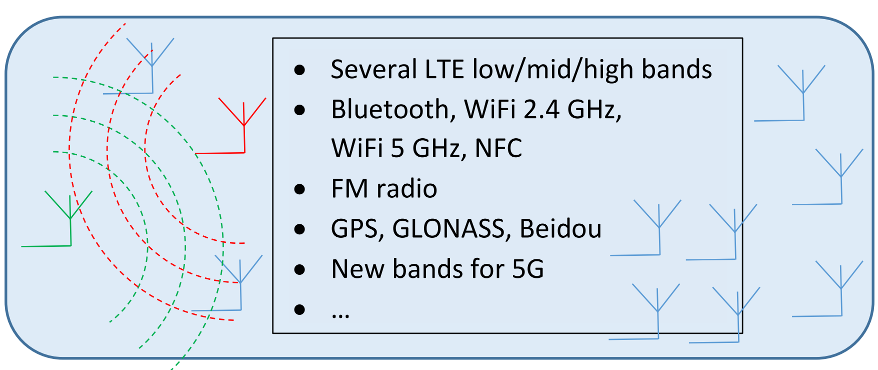

Figure 1. Illustration of a portable mobile device and the many antennas and radio systems in it

The different radio systems are efficiently isolated by filters in the RF front ends, but there are several reasons why the antenna-to-antenna coupling must be dealt with care. First, there are MIMO systems and diversity antenna groups that share the same frequency bands. Second, strong coupling at a harmonic frequency may cause an intermodulation product of transmitter A being coupled to receiver B's operation band – the filters may also exhibit similar harmonic periodicity as the antenna pass bands. Third, the filter stopbands are typically designed for a 50 Ohm environment, and far from the designed passband the antenna can be anything but 50 Ohms, and therefore the stopband is usually good only close to the passband. This in turn means that the filters of system A may leak coupled power from system B into system A, causing desensitization of system A and power loss for system B. Fourth, the radiation efficiencies of a compact system's antennas may be quite poor. This means that the nearby antennas dissipate a significant portion of the coupled power even if the corresponding radio systems are perfectly filtered.

All these phenomena call for a novel, comprehensive analysis and optimization methodology for the multi-antenna systems.

Why existing analysis methods struggle?

Traditionally, three different antenna system analysis approaches are used:

1. Measurement-based approach: the S-parameters of the multiport system are characterized by a multiport Vector Network Analyzer (VNA), and the radiation patterns for each antenna are measured in anechoic chamber using a laborious measurement setup.
2. A general-purpose RF simulator, which can analyze the circuit aspects of antenna systems, but typically is not aware of the radiation-related quantities and efficiencies.
3. Electromagnetic (EM) simulation of the antenna system, which replaces the laborious measurement setup with a flexible virtual model, and usually the same EM software packages provide also lots of post-processing functionality for the simulated data.

A common problem with all of the above methods is the proper treatment of mutual coupling terms in a multi-antenna system. An equally burning problem for method 1 is the correct calculation of radiation efficiencies, because they depend upon each port's termination and require superposition of the 3D radiation patterns. Moreover, the radiation efficiency data is typically defined on different frequency grid than S-parameter data, possibly further complicating the total efficiency calculation. To sketch the scale of the coupling challenge, a rather typical 12-antenna system involves 132 mutual coupling terms that need to be written *manually* in equations that calculate the total efficiency.

EM simulators are usually somewhat more prepared for the multi-antenna problem, and they can calculate the total efficiency for each antenna, taking into account the coupling losses and the termination-dependent radiation efficiencies. Quite understandably, EM simulators only support radiation patterns from their native projects in native format, as - unfortunately - there is no standardized format for radiation patterns. This means that in practice each EM simulator has its own format for radiation patterns, and the pattern data cannot be exchanged between the tools the same way as for example S-parameter files.

But EM simulators have their blind spots as well. When it comes to antenna port terminations by matching circuits, filters etc., one needs circuit components and their models. Usually the RF simulators have more attention to component libraries, and realistic component models are equally important in analyzing the total system. Moreover, it is not all about total efficiencies, it is also about component-wise losses, voltages and currents at different parts of the connecting circuitry. In such analyses, the RF simulators are again strong – but they are undoubtedly limping when it comes to analysis of the total efficiencies.

To summarize in a bit simplistic way, EM simulators are strong from antenna inputs towards free space, and RF circuit simulators are strong from amplifiers up to S-matrix ports representing antenna inputs. Is it possible to have an analysis methodology that simultaneously combines these two sides of the coin?

New approach

A new software solution has been developed that combines the strengths of EM- and RF circuit simulators in analyzing the status of a multi-antenna system, *boosted by automated circuit synthesis* to optimize the system's performance.

Often, the performance of an antenna system needs to (and can) be improved by relatively simple matching and decoupling circuits. But to do it right, the system performance must be correctly characterized taking all of the above into consideration.

The new approach is implemented in the Optenni Lab RF design automation software platform, and after years of development it has reached the maturity where it seamlessly links the EM- and circuit aspects of the multi-antenna problem. Looking towards the EM domain, in addition to the multiport S-parameter matrix, 3D radiation patterns in *several industry standard EM simulator formats* are supported. The guiding philosophy is "most suitable tool for each problem", and therefore our Optenni Lab platform is as neutral as possible regarding the data input and output. For a given geometry of an N-antenna system, the NxN S-parameter matrix and the N radiation patterns (over frequency) represent a complete characterization of the linear system "from antenna inputs towards free space" – in other words, EM simulation cannot provide any new information for the system characterization. Therefore, S-parameters and radiation patterns have knowingly been chosen to represent the "EM side of the coin".

The linearity of the multi-antenna system allows weighing and summing the fields according to the voltages/currents at antenna inputs, resulting from circuit analysis involving matching components, filters, different terminations etc. at the antenna ports, but also involving port to port power coupling, characterized by the S-parameter matrix. The total radiation pattern obtained by weighted superposition of all the antenna patterns allows the exact calculation of each antenna's radiation efficiency. This process of combining circuit simulation quantities (voltages, currents) with EM simulation quantities (radiation patterns) is the link between these two domains.

As stated before, neither modeling domain is sufficient alone: circuit simulation domain completely ignores the radiation efficiencies, which can be as low as 30% or less in a practical scenario for some antennas. EM simulation domain misses the proper weighing of the individual radiation patterns, causing inaccuracy in the radiation efficiencies. Often even more important is that the EM simulation domain misses the losses in the circuit components between the amplifier and the antenna input, which can also account for high percentage of the total losses.

Because the combination of these modeling domains is obviously useful, several tools provide some level of integration or co-simulation between them. There are three points, however, that make the Optenni Lab approach fundamentally different from all of the previous solutions: 1) agnosticism with respect to EM simulation tool used; 2) incorporation of automated topology synthesis "on the circuit side"; 3) specifically designed knowledge of the antenna quantities from system perspective.

Why topology synthesis?

The highly coupled nature of a compact multi-antenna problem implies that "everything depends on everything", in other words the antennas must be matched and optimized in concert. Any choice for the matching circuit for antenna A has an influence on which matching circuit is best for antennas B, C, D… and so on. Because the number of possible matching topologies for a multiport problem is an exponential function of the number of matching components and the number of ports, brute force is not a working approach even for an automated synthesis (let alone manual setup for each topology!), but a number of justifiable, simplifying assumptions need to be done to make the problem manageable. The relevance of such assumptions eventually determines the efficacy of the method to solve coupled multiport matching problems, but it is important to note that a topology synthesis without the ability to characterize the system correctly is mostly wasted effort. Therefore, the *analysis* capability must precede *synthesis and optimization* capabilities, and from design platform development perspective these are almost independent platform properties, while obviously intimately linked from the user perspective.

Synthesis solutions in Optenni Lab

The basic form of an automated synthesis solution is a "black box" in front of an antenna that generates a number of optimized matching circuits. These matching circuits are optimized for total efficiency, i.e. the component losses and antenna radiation efficiency are taken into account in the synthesis, and various breakdown metrics are available like mismatch loss, total TX/RF chain losses and total efficiency. This data is also illustrated in a graphical Power Balance diagram. Figures 2 and 3 illustrate the consequences of a common optimization trap when focus is on S_{11}. Good impedance match does not guarantee good performance. Therefore, it is important that the optimization tool is aware of the actual quantity of interest.

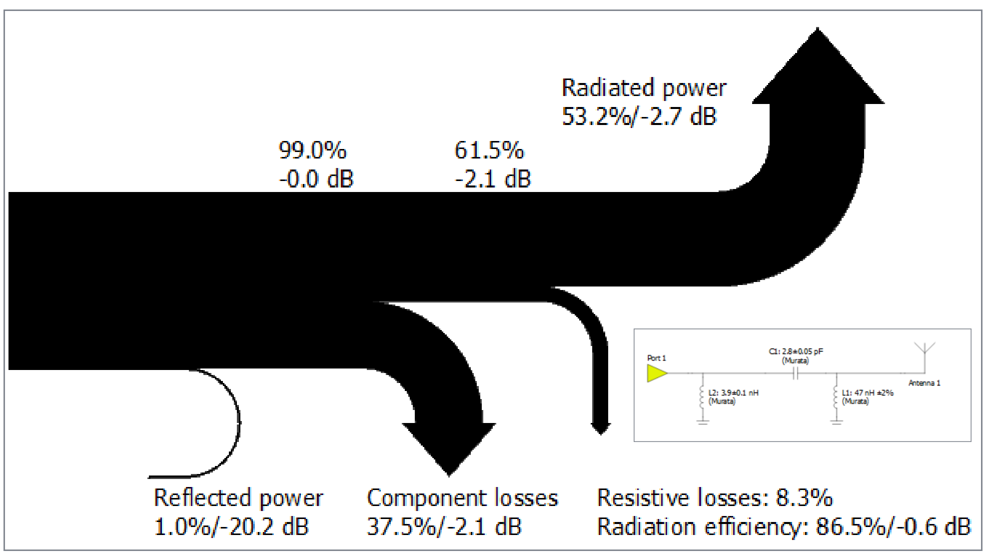

Figure 2: Power Balance of an antenna with optimized return loss. Note the high component losses.

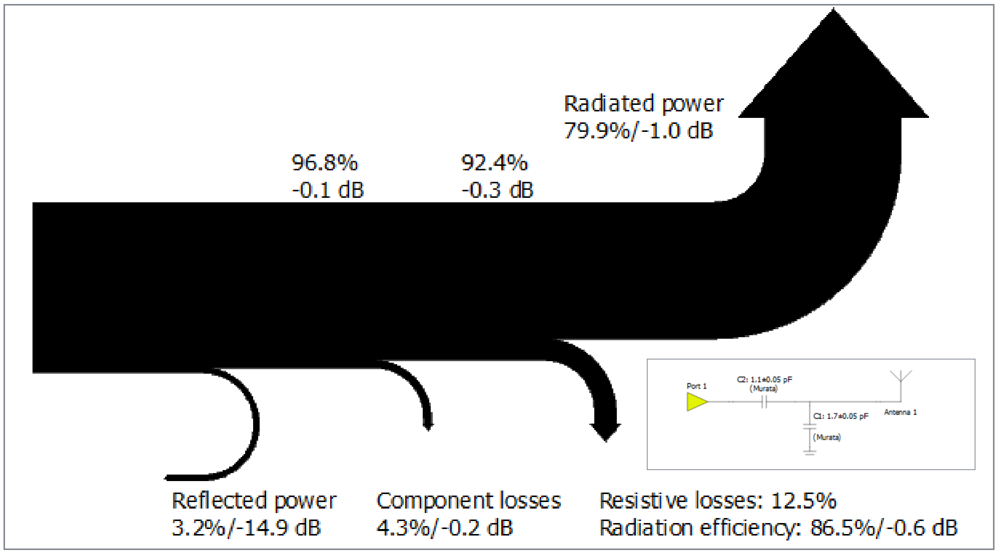

Figure 3: Power Balance of the same antenna than in Figure 2 with optimized total efficiency. Note the much higher radiated power yet simpler matching circuit.

The discrete component synthesis of Optenni Lab uses real component models from many component vendor libraries. This enables accurate calculation of losses and voltages/currents for each matching component. Moreover, the tool is aware of the component ratings, and warns the designer for a possible burndown if the rating is exceeded.

To support high power and high frequency designs, microstrip synthesis is also supported, with automatically added discontinuity models. Hybrid designs are also supported, incorporating both discrete components and microstrip lines, when e.g. DC block capacitors are employed, or lumped series inductors are replaced by microstrip segments.

An important practical concern in the matching circuit design is the PCB layout. Optenni Lab supports incorporation of arbitrary layout through an EM-simulated multiport S-parameter model representing the layout section in the PCB (Figure 4). A simplified layout representation can also be built using microstrips. In both cases the synthesis key is a component called *Generic reactance*, which emerges as either an inductor or a capacitor. Therefore, when the layout is fixed for a certain shape – e.g. Pi or T topology – there still are 2^N alternative combinations of L and C. Optenni Lab synthesizes all of them, and ranks the optimized circuits in a list according to the performance.

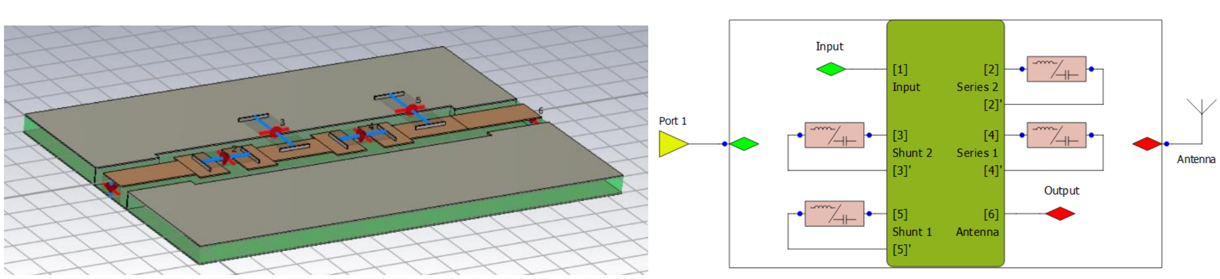

Figure 4. Matching circuit PCB layout EM model and its use in Optenni Lab with Generic reactance components

Usually there are other components as well in the RF chain that need to be considered, such as baluns, filters, transmission lines/cables and switches. These RF-components are designed to work in 50 Ohm environment, but as discussed earlier, the antenna impedance can deviate significantly from 50 Ohms, and the individual components are no longer in their designed impedance environment. Optenni Lab provides a *Synthesis block* component to be used in several interfaces along the RF chain, to allow the complete chain optimization for the design goals, e.g. total radiated power maximization on passband(s) and desired stopband performance elsewhere. A schematic in Figure 5 illustrates the setup.

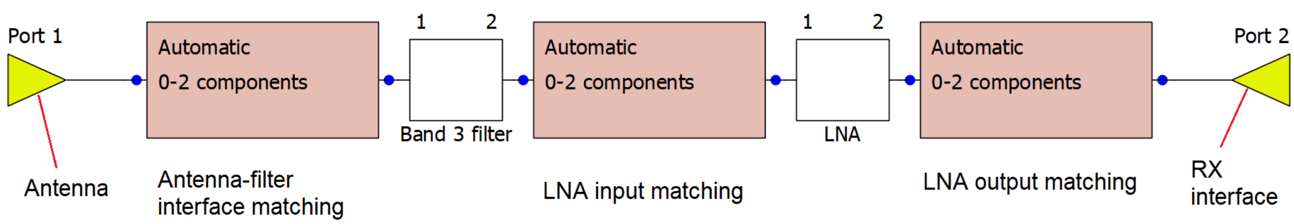

Figure 5: Example use of the Synthesis block "black boxes" in receiver RF chain.

A relevant design concern is also the result sensitivity with respect to small variations in matching component values. Sometimes the nominally optimal solution looks really good from a quick inspection, but turns out to be useless because small changes in component values render the system efficiency poor. Figure 6 shows one example, where the "best" solution performance degradation due to 5% component tolerances is enormous. In contrast, the topology that ranks #3 in the nominal performance, turns out to provide most stable response. Optenni Lab provides this tolerance sensitivity re-sorting *automatically*, which is a big saving compared to manual analysis work: there can be tens or hundreds of candidate topologies to choose from.

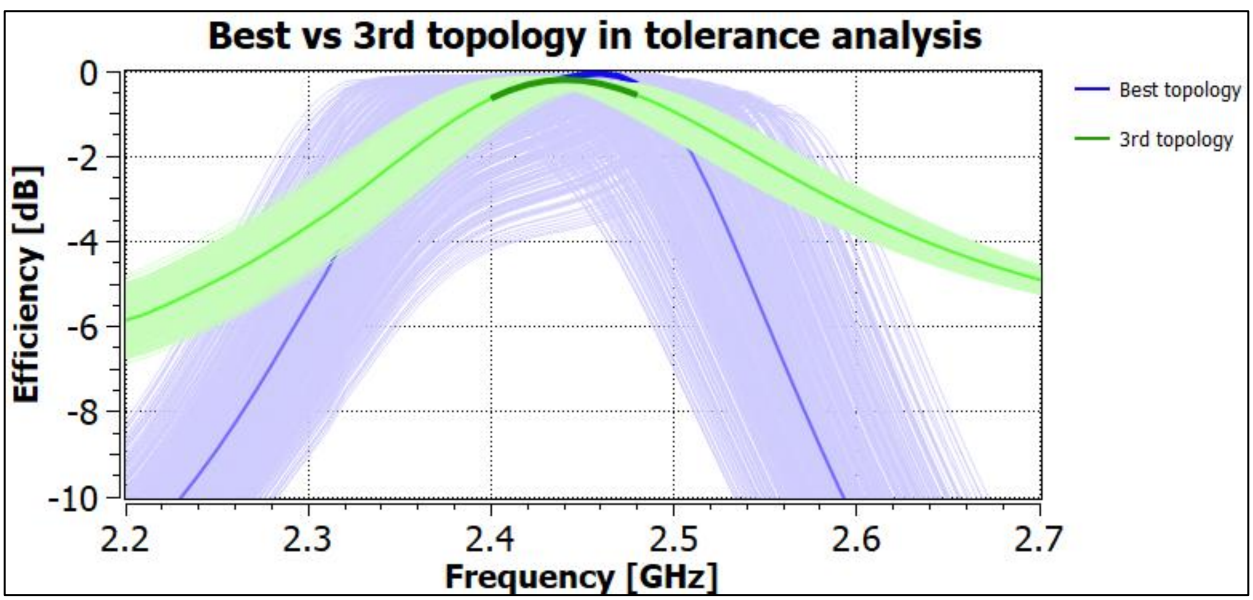

Figure 6: Nominally best topology (blue curves) can be catastrophic due to sensitivity to component values. A minor compromise in nominal performance may provide much more stable solution.

Multi-antenna specific analysis and synthesis capabilities

Traditional multi-antenna design relies on implementing resonances of the radiating elements at the wanted frequencies, and antenna-to-antenna isolation is achieved by physical separation, which is limited by industrial design considerations. For compact devices, the possibility for physical separation is limited, and coupling can be a serious design challenge. Moreover, for an optimal design, it is important to be able to calculate the radiation pattern and radiation efficiencies *of the matched system*.

When coupling is significant, the excitation at antenna A induces currents on antenna B, which in turn influence the far-field radiation pattern of antenna A. These induced currents depend upon antenna B port termination. Instead of calculating the induced distributed currents on antenna elements, the induced currents on antenna feed points are solved, and total radiation pattern is calculated by superposition of the complex far fields. The radiation efficiency is then calculated from the total far field.

Let us consider the following design challenge. We are set to design an all passive 3-band multi-antenna system:

- 3GPP band 7 (2500 – 2690 MHz)
- 3GPP band 1 (1920 – 2170 MHz)
- GPS L2 (1215 – 1239.5 MHz) and Galileo E6 (1260 – 1300 MHz)

In a traditional approach, to have good element-to-element isolation, the elements should be multiple centimeters apart. In contrast, in the example design depicted in Figure 7 some parallel lines of the design are only some 0.5 cm apart due to the limited space reserved for the antennas.

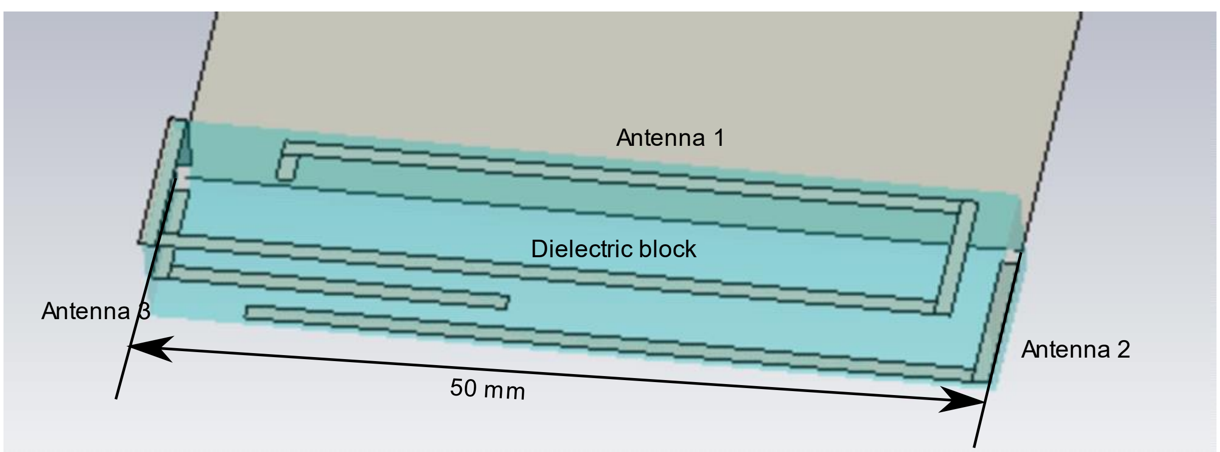

Figure 7: A typical, multi-antenna handheld device system, in which the antennas are sharing the same volume in the device chassis.

As we study the initial performance of the system, shown in Figures 8-9, we see some problems: the resonances of the antennas are shifted due to a change of the supporting dielectric material, and the coupling losses are quite high, which is not very surprising for such a tight design. A quantitative assessment of the losses would be difficult from S-parameters alone. Optenni Lab's Power balance diagram reveals the state of the design very clearly: all antennas are mismatched, and antenna #2 is strongly coupled to the other antennas.

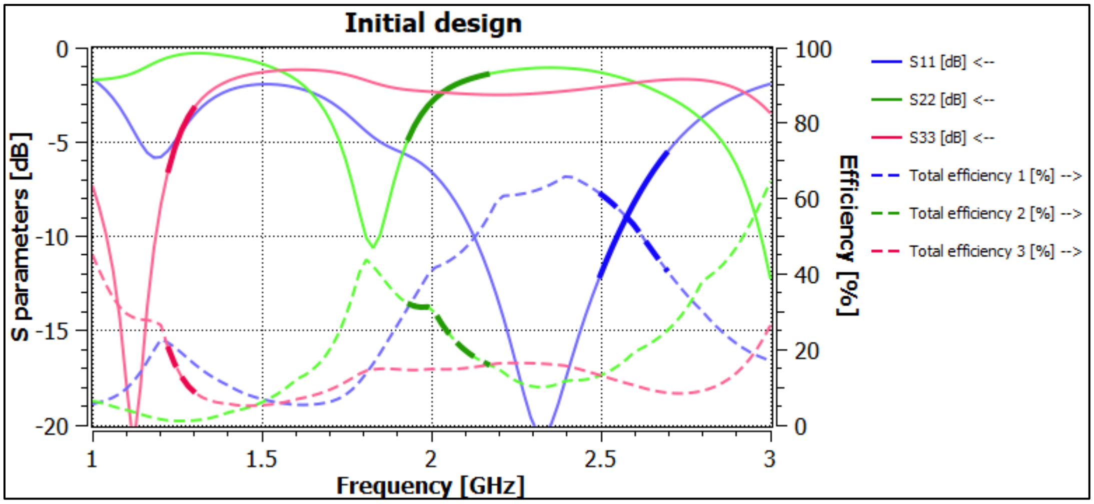

Figure 8: S_{nn} and total efficiencies of the initial design

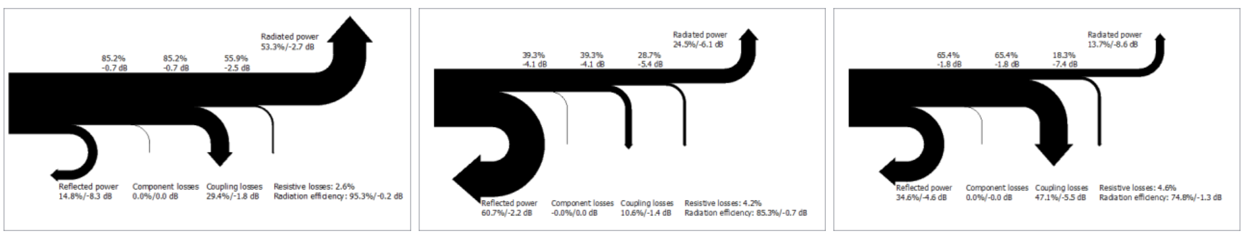

Figure 9: Power balance diagrams reveal the problems in the design quickly: the antennas are not only de-tuned but also strongly coupled. Antenna #1 is on the left, antenna #2 in the middle and antenna #3 on the right.

If we again solve the problem by optimizing the return loss of each port, we neglect the other loss mechanisms that are possibly dominating: component losses, coupling losses and radiation efficiency. The result of such "S_{nn}-optimization" using very low-loss matching components from Coilcraft 0402DC library (for inductors) and Murata GJM15 library (for capacitors) is shown in Figure 10. The Power balance diagrams of this design is shown in Figure 11.

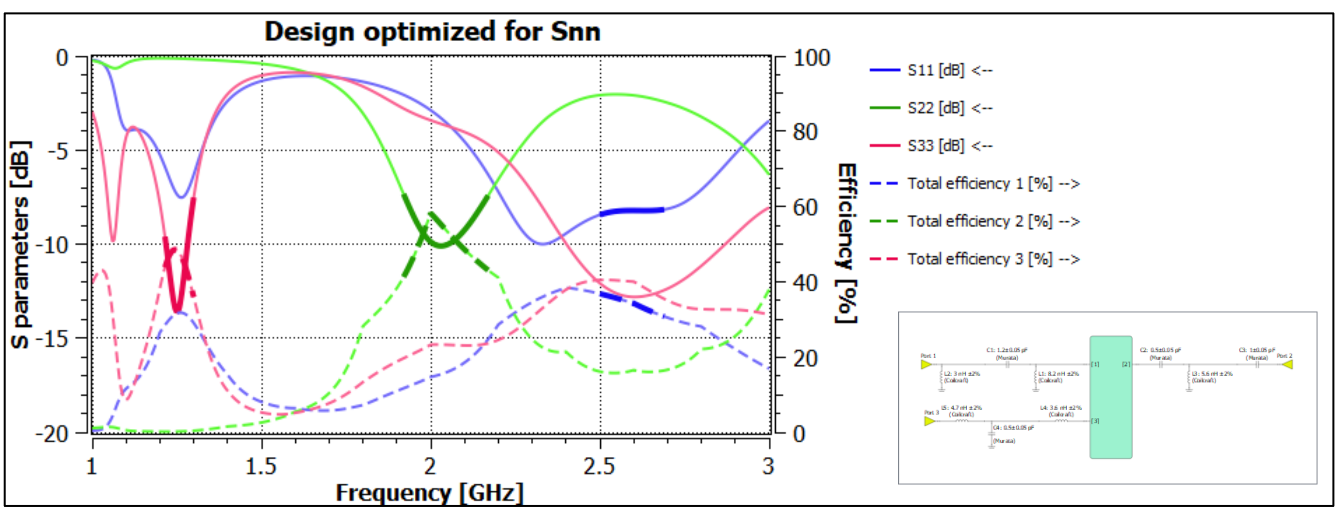

Figure 10: S_{nn} and total efficiencies of the design optimized for return loss

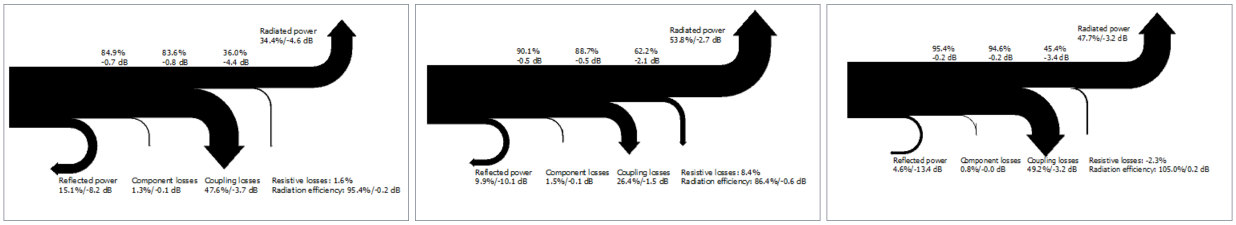

Figure 11: Optimization for return loss finds a solution that maximizes the antenna-to-antenna power transfer, i.e. coupling loss. The total efficiency is anyway improved, except for antenna #1.

The result is logical but not what we want. Instead, using the default Optenni Lab settings for optimization of the total efficiencies results in an entirely different set of S-parameters, efficiencies and loss breakdown. We can go a step further and let Optenni Lab search for a robust solution with respect to component tolerances, the same way as was discussed in the single-antenna context earlier. The results are shown in Figures 12-13, and the total efficiency averaged over bands and antennas is 2.2 dB higher than after the return loss optimization, mainly due to reduced port coupling. The much smaller coupled power means also less cross-band receiver de-sensitization and higher SNR for the whole system.

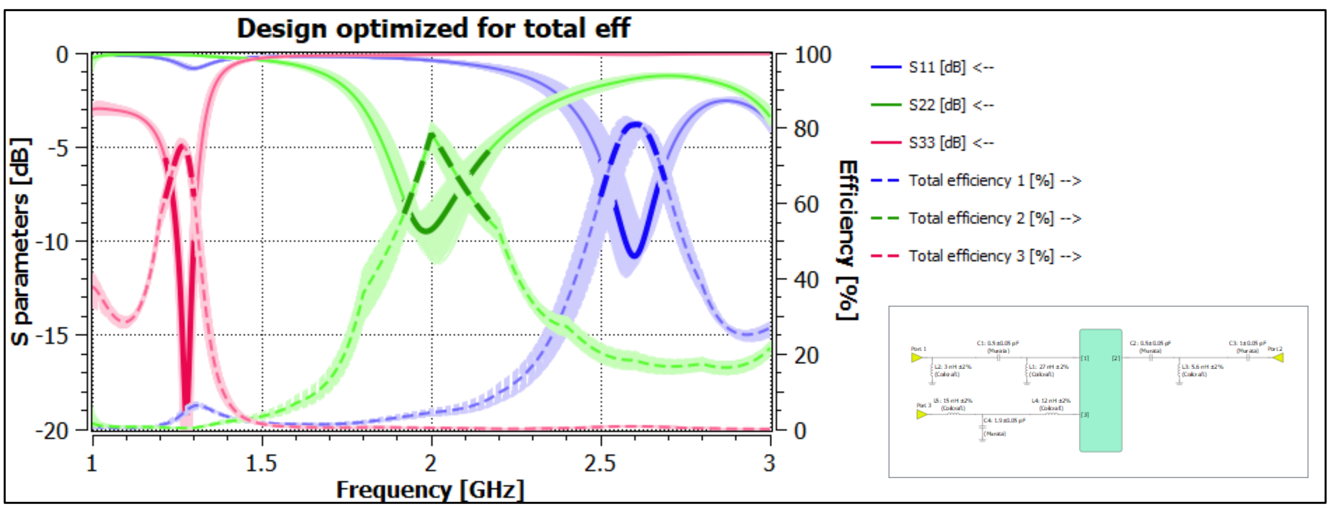

Figure 12: S_{nn} and total efficiencies of the design optimized for efficiency. The response variation due to matching circuit component tolerances is also depicted. The efficiency curves clearly reveal the mutual filtering that is automatically generated by the optimization process.

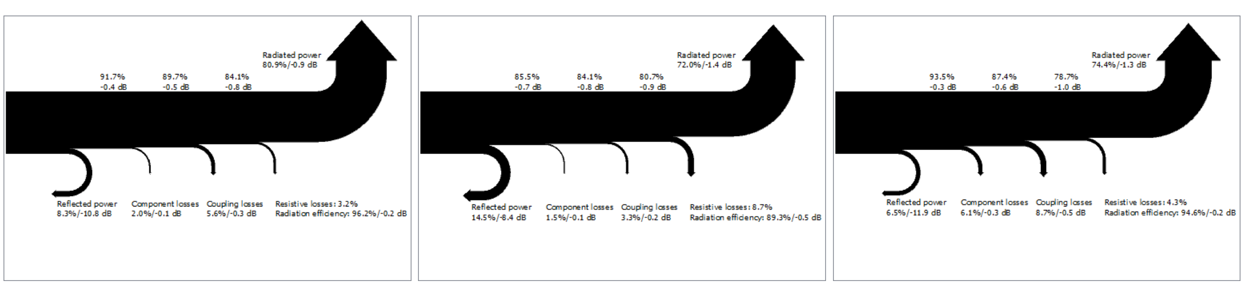

Figure 13: Power balance diagrams show that most improvement is achieved by minimizing the coupling losses

Conclusions

In this article we discuss a new approach for antenna system optimization. One of the key points is that traditional solutions involve nearly opaque design domain boundaries, regarding electromagnetic full-wave simulation and circuit simulation. The traditional linking of the two worlds occur through S-parameter matrix, but it is shown to be an incomplete characterization for antenna systems, in particular for multi-antenna systems. The reason is that the radiation efficiencies are not characterized by S-parameters, so the traditional circuit simulators are missing that information altogether in the system performance simulation. On the other hand, in coupled multi-antenna problems, the radiation patterns and efficiencies depend upon circuits that connect to the antenna ports, so the EM-simulators can’t characterize the radiation efficiencies either, without looking “to the other side through the S-parameter boundary” i.e. to the circuit side. This is obviously true for the total system efficiency calculation, loss breakdown and tolerance analysis as well.

This new approach is implemented in Optenni Lab RF design automation platform, and one can call it antenna-aware circuit simulator. The antenna-awareness means that it uses as compact characterization as possible of the EM design domain that is necessary for an exact description of the system. This characterization is routinely available from commercial EM tools, and it consists of S-parameter matrix and far-field complex radiation patterns of each antenna in the system. Due to the universal nature of this necessary and sufficient set of data, Optenni Lab is configured to support several major EM simulator’s far-field pattern data formats.

Another unique aspect in this new approach is automated and fully integrated synthesis routines for matching circuits, and fast, parallelized optimization of a vast number of synthesized candidate topologies for total efficiency. Because Optenni Lab is antenna-aware, it understands all loss contributors without any user advice. This is particularly helpful with multi-antenna problems where the number of coupling terms alone easily exceeds 100. Plots for the relevant system metrics are automatically set, and the Power balance diagram is a great help to assess the system performance, and to document project results. Component libraries with realistic models and the tolerance analysis with the possibility to automatically select least sensitive designs complete the palette, making this new approach a true game-changer in the antenna system design arena.