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Full Wave Matching Circuit Optimization Shortens Design Iterations

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Full wave matching circuit optimization (FW-MCO) is a new technology that combines full wave, 3D electromagnetic (EM) simulation with circuit optimization into a novel approach for solving an age-old RF problem: determining which component values provide the desired match for a given matching network layout. Gone are the days of soldering components in and out of a prototype, trying to achieve the desired performance. This article describes the design process using the design of a matching circuit for a GPS-Bluetooth antenna.

Matching network design is challenging, and RF engineers lack a robust tool for choosing which component values to plug into a matching network layout. Testing a single configuration at a time is expensive, slow and does not result in optimal performance. Existing schematic-based software tools help designers choose a circuit topology to match an antenna according to design goals, such as maximizing efficiency. At low frequencies, the predicted match from a schematic can be comparable to the measured performance of a physical circuit because the connections are very short in terms of wavelengths, the loss is low, and parasitics and coupling with other parts of the geometry are minimal. At higher frequencies, perfect wires become RF components like radiators or lossy transmission lines. Traces couple with each other and with other parts of the geometry. Since the EM interactions are usually more complex than what is represented in the schematic, the resulting physical performance can vary from what the schematic predicts.

Fortunately, full wave electromagnetic simulation captures these complex interactions, so it is possible to perform an optimization which will find the proper circuit component values without trial and error. FW-MCO addresses this missing link in the design process by modeling the RF effects and utilizing that information in the component selection process.

MATCHING NETWORK DESIGN WORKFLOW

The workflow for designing any new device is iterative, with multiple false starts, branches and challenges. As engineers gain an understanding of the problem areas and develop more efficient processes, workflow linearity increases and managers shorten their expecta-

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Fig. 1 Unmatched GPS-Bluetooth antenna.

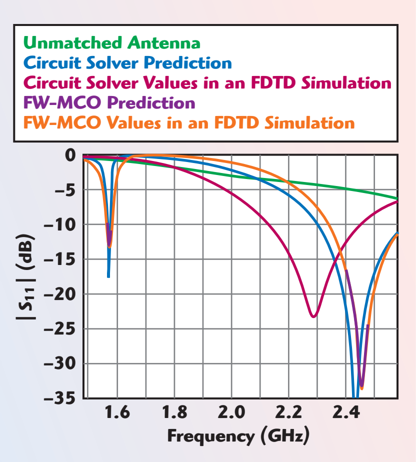


Fig. 2 Antenna $|S_{11}|$ for various cases.

tions for design cycle lengths. Ignoring the iterative loops, the following are the four main steps to design a matched antenna.

Starting with an unmatched antenna — either a physical prototype or CAD model — an RF engineer's first task is to determine the input impedance and corresponding S_{11} of the radiating structure. The GPS-Bluetooth antenna shown in ***Figure 1*** will be used for this discussion. Two main techniques are used for determining its input impedance. Historically, and in many cases still preferred, a network analyzer measures the impedance in a lab. Recently, the use of full wave, 3D EM simulation has become more popular; Remcom's XFdtd and ANSYS' HFSS have become commonplace for characterizing an antenna. ***Figure 2*** shows the reflection coefficient of the unmatched antenna.

With S-parameter data for the antenna, the second step employs circuit solvers such as Optenni's Optenni Lab and Keysight's ADS. These have schematic-based editors for building matching network topologies, where the schematic comprises the list of components and the nodes that connect them. Circuit solvers analyze the schematic by maintaining voltage and current relationships across the components and at the nodes. ***Figure 3*** shows a four element match-

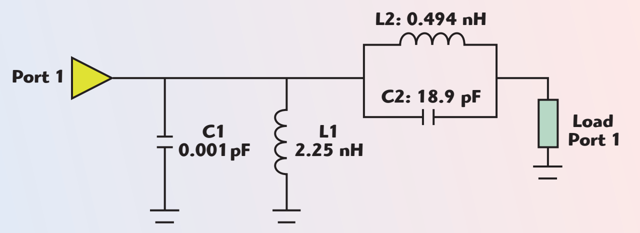


Fig. 3 Topology for the GPS-Bluetooth antenna's matching network.

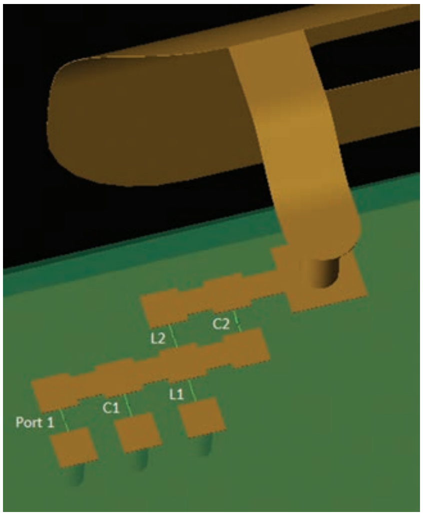


Fig. 4 Matching network layout.

ing network topology that provides an acceptable match in the GPS and Bluetooth bands. The corresponding S-parameter prediction from the circuit solver is also shown in Figure 2.

Once a matching network topology and initial component values have been generated, the engineer converts the schematic-based topology to a physical layout on a printed circuit board (PCB). Depending on the engineering team's process, mechanical engineers may get involved in the layout process, utilizing software products from Cadence or Mentor Graphics. ***Figure 4*** shows the matching network layout for the GPS-Bluetooth antenna (the lumped components are shown as green lines connecting the copper traces).

At the completion of step three, the RF engineer has an updated physical prototype or CAD model that includes the matching network layout. The layout will reflect the initial lumped component values determined from the circuit solver in step two. If the device is operating at a low enough frequency or the antenna has been isolated from the matching network, a measurement or full wave simulation of the updated prototype will show good agreement with the circuit solver, and the engineer moves forward to product testing. At higher frequencies, a fourth step in the antenna design workflow is generally required, because the updated prototype does not perform as the circuit solver predicted. This difference can be seen by comparing the circuit solver prediction to the finite difference time domain (FDTD) simulation in Figure 2.

In the fourth step, the RF engineers determine the final component values that provide the desired performance with the matching network as it is laid out on the PCB. Until recently, no tools were available to effectively address this problem, so engineers relied on costly techniques that provided sub-optimal performance, such as soldering components in and out of a prototype. FW-MCO technology overcomes this challenge by allowing RF engineers to consider thousands of component combinations and determine the optimal antenna performance. ***Table 1*** shows the significant difference between the component values determined by the circuit solver and the optimal ones chosen by FW-MCO. The final two plots in Figure 2 show that the predicted S-parameters from FW-MCO match the validation from an FDTD simulation.

FW-MCO

Specifically created to address the final step in the matching network design workflow, FW-MCO selects the optimal set of lumped component values from the list of allowable components. It uses efficiency and/or S-parameter goals to rate one set against another, accounting for the myriad of electromagnetic phenomena affecting the matching network's performance. There are two main steps to FW-MCO: system characterization and component selection.

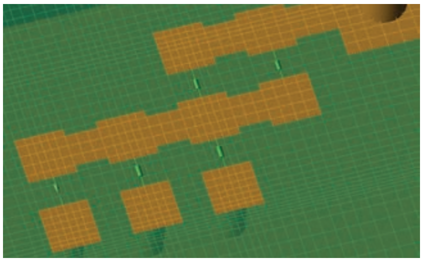
TABLE 1

SELECTED COMPONENT VALUES

	Circuit Solver	*FW-MCO*
C1	0.001 pF	0.2 pF
C2	18.9 pF	5.6 pF
L1	2.25 nH	1.7 nH
L2	0.494 nH	0.6 nH

FW-MCO's system characterization step utilizes full wave, 3D electromagnetic simulation to analyze the matching network's physical layout and surrounding environment. Unlike a circuit solver, FW-MCO doesn't look at the matching network as a set of lumped components that are connected to nodes by defined transmission lines. Instead, FW-MCO treats each lumped component as though it is plugged into a system made up of a 3D environment containing PCB traces, radiating elements, plastic housing, antenna loading, etc. ***Figure 5*** shows how circuit components are plugged directly into the surrounding physical geometry via the FDTD mesh. The system characterization accounts for field interactions within the matching network, between the matching network and radiating antenna(s) and throughout the entire device. Once characterized, the system is represented by a response matrix that defines the interaction of each component with the system and, consequently, each other. Since FW-MCO abstracts the system into a response matrix, it implicitly accounts for the physical layout of the matching network. For example, it is not necessary to explicitly specify the length of a transmission line because that information is contained in the response matrix.

Once the system has been characterized, it is possible to select any set of components and determine the associated antenna match based on the response matrix without needing to rerun a full wave simulation. FW-MCO's second step, therefore, becomes an optimization problem, where the optimal component values are determined. The RF engineer defines ranges of allowable component values and chooses desired goals for maximum optimization. The list of allowable component values represents the bin of components that can be used in the design. Often, this is equivalent to the list of components available from a component supplier. An individual component can be passive or active; the requirement is that the component be represented in the frequency domain. This provides the flexibility to populate the list with inductors, capacitors and tunable components that are treated as ideal components or realistic ones defined by an *.s2p file. The component values can vary continuously or be restricted to a finite number of fixed values within the desired range, representing actual values available from the manufacturer. Radiation efficiency, system efficiency, S-parameters or a combination can be used to define the goals. In addition, the RF engineer needs to provide the associated threshold over a specified frequency range. For example, one goal could be to find a set of component values that provides greater than 68 percent radiation efficiency over the desired LTE bands.

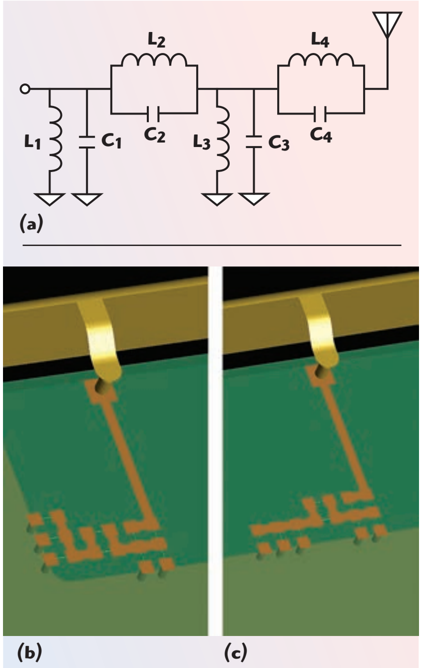


▲ *Fig. 5 Lumped components simulated in a FDTD mesh.*

The optimization treats each component as a variable that can take on one value from the associated list of allowable component values. As such, the optimization algorithm needs to be able to handle multiple variables and be able to identify the global minimum from the multitude of local minima. Particle swarm optimization and genetic algorithms are both able to make this distinction. At the conclusion of the optimization, the optimal set of component values will be available. If some goals fail to be met, then the RF engineer needs to circle back in the workflow and make an adjustment. That may entail changing the physical layout of the matching network, or the change may be as far back in the design process as modifying the antenna structure. If each goal has been met, then these components can be considered the final values and plugged into the prototype for validation and product testing. Since system characterization was completed with full wave, 3D EM simulation, a close match between the FW-MCO prediction and measured results can be expected.

FW-MCO VS. CIRCUIT SOLVERS

While FW-MCO and circuit solvers are both used for matching network design, they are primarily differentiated by the data available to them. For a single port antenna, a circuit solver is provided the source impedance, S_{11}, and radiation efficiency as inputs. When the matching network schematic is analyzed, circuit solvers are limited because they use empirical formulas to maintain voltage and current relationships across the components. They cannot account for field interactions between components, between the components and active antennas and between the components and the rest of the device. FW-MCO, on the other hand, captures all the field interactions that are computed by the full wave EM simulation and selects component values based on that information. As an example, consider the eight element matching network topology in ***Figure 6a***. Physically, it can be laid out as shown in ***Figure 6b*** or ***6c***. While a circuit solver will only return one set of initial component values for this topology, FW-MCO will compute different response matrices for the two different layouts. This leads to the selection of two sets of component values to match the corresponding physical layouts.



▲ *Fig. 6 Eight element matching circuit topology (a) with two physical layouts (b and c).*

FW-MCO does not replace circuit solvers in matching network design. The two technologies are appropriate for different steps in the workflow. Circuit solvers identify the appropriate topology and provide initial component values in the middle of the workflow. At the end, FW-MCO analyzes the physical layout and returns final component values.

APPLICATIONS

Traditional LC matching network design for a single antenna in free space is used extensively in device design and is readily supported using the FW-MCO approach previously outlined. Consumer demands for reliable connectivity and high data rates, however, are pushing RF engineers beyond traditional design. Fortunately, the flexibility of FW-MCO supports the design of multiple antenna loading configurations and multiple antennas.

Many devices operate under different antenna loading configurations. Consider any hand-held device, where the antenna loading will be different when the device is in free space or being held in a hand. These two configurations lead to different input impedances, so a matching network that passes requirements for free space operation may not be sufficient when the device is held. For simpler, cheaper designs, the RF engineer may use a traditional matching network with LC values that best fit both cases. A more advanced solution would be to incorporate a tunable component into the matching network and a proximity sensor at the device level. In a 3D EM simulator, a phantom hand model would be included in the simulation space for the hand-held configuration. This will lead to different field interactions with the components than the free space configuration. Remember that the response matrix is used to characterize all field interactions affecting the components of the matching network. Therefore, two response matrices are needed to capture the field information for the two loading configurations, which will serve as inputs into a single optimization.

In the advanced case with tunable components, the proximity sensor would be used to detect whether the device was operating in free space or operating while being held. The tunable component's state would then be changed depending on the loading configuration, and this would change the matched impedance. FW-MCO uses similar logic to tie the loading configuration information in the response matrix to the tuner states in setting up the optimization. The goals would be defined to generate better than 93 percent and 75 percent radiation efficiency in the LTE bands for the free space and hand-held response matrices, respectively. As output, the optimization would return two tuner values, one associated with each response matrix. If there were LC components in the matching network, the optimization would also return their fixed values independent of the loading configuration.

The design of multiple antennas also provides a challenge to RF engineers because energy from the active antenna can be lost in the passive antenna, instead of being radiated. This is known as "suck out" and can be identified through S_{21} or reduced radiation efficiency. Using FW-MCO to select optimal component values that reduce suck out is straightforward. The two antennas and corresponding matching networks would be included in the 3D EM simulation space. A single response matrix simulation would characterize the system and determine field interactions affecting all components. Finally, goals would be defined that simultaneously maximized radiation efficiency when antenna 1 was active and minimized S_{21}. Depending on device design decisions, FW-MCO could also be used to identify tunable components that create a poor match at antenna 2 when antenna 1 is transmitting, yet a good match when antenna 2 is transmitting.

CONCLUSION

A new technology, full wave matching circuit optimization, fills the last gap in matching network design. Unlike schematic-based circuit solvers, it accounts for all electromagnetic field interactions with components. Using this information, FW-MCO is able to analyze thousands of component combinations to determine the optimal set that meets design requirements. As the complexity of matching network design increases to support the latest communication requirements, FW-MCO will become a necessity because the number of permutations will be unwieldy without optimization techniques. ■