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Abstract

Direct, gradient-based, optimization-driven electromagnetic design is studied. Focusing upon a double folded stub microstrip filter, we explore design characteristics for coarse grids. EM models: EMC for fast computations and corresponding EMF for more accurate simulations are compared. The EMC model, useful when circuit-theoretic models may not be readily available, permits rapid exploration of different starting points, solution robustness, local minima, parameter sensitivities, yield-driven design, and other design characteristics within a practical time frame.

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SUMMARY

Introduction

We present new results of microwave filter design with accurate electromagnetic (EM) simulations driven by powerful gradient-based optimizers. We go far beyond the prevailing use of stand alone EM simulators, namely, validation of designs obtained using empirical circuit models. Feasibility of performance-driven and yield-driven circuit optimization has already been shown in previous pioneering work [1, 2].

Simulation time using EM simulators can be significantly decreased if the grid used for numerical EM modeling is coarse (EMC). A coarse grid decreases the accuracy of EM analysis but qualitative, and often quite accurate quantitative, information about the behaviour of the circuit may be exploited. The EMC model allows us to explore different optimization starting points, solution robustness, local minima, parameter sensitivities and statistics, and other design characteristics within a practical time frame. As design data accumulates we can correlate the EMC and more accurate fine grid EM simulation models (EMF). The bulk of CPU intensive optimization can then be carried out on the inexpensive EMC model. The final solution is always verified and fine tuned, if necessary, by an EMF model.

We perform nominal and yield optimizations of the double folded stub filter [3] using an EMC model and verify the results with an EMF model. Encouraged by good consistency of both results we use the EMC model to perform otherwise very CPU demanding analysis of robustness of our optimized solution.

In our work we utilize the OSA90/hope optimization environment [4] with the Empipe [5] interface to the ***em*** field simulator from Sonnet Software [6]. This smart interface addresses challenges of efficiency, discretization of geometrical dimensions, and continuity of optimization variables through efficient on-line response interpolation w.r.t. geometrical dimensions of microstrip structures simulated with fixed grid sizes, smooth gradient evaluation for use in conjunction with the proposed interpolation, and storing the results of expensive EM simulations in a dynamically updated data base.

EMC Optimization of the Double Folded Stub

We optimized the double folded stub filter of Fig. 1. The x and y grid sizes for EMC simulation are chosen as $\Delta x_C = \Delta y_C = 4.8$ mil. The EMF simulation used to verify the EMC results uses a grid size of $\Delta x_F = \Delta y_F = 0.8$ mil. All five geometrical parameters L_1, L_2, W_1, W_2 and S are designable. The design specifications are as follows.

$$|S_{21}| > -3 \text{ dB} \quad \text{for} \quad f < 9.5 \text{ GHz and } f > 16.5 \text{ GHz}$$

$$|S_{21}| < -30 \text{ dB} \quad \text{for} \quad 12 \text{ GHz} < f < 14 \text{ GHz}.$$

For the EMC case the time needed to simulate the filter at a single frequency and an arbitrary point is about 10 CPU seconds. This includes automatic response interpolation carried out to accommodate off-the-grid geometries. The corresponding time for EMF is approximately 15 minutes.

To further refine the EMF solution we applied our new space mapping (SM) optimization technique [7]. The SM technique is based on parameter space transformation and aims at finding the image of the EMC optimal solution in the EMF parameter space. The main advantage of the SM method is that it requires only a few EMF simulations. The optimized and refined SM results are listed in Table I. Fig. 2 shows the $|S_{21}|$ response before and after minimax optimization using the EMC model. Fig. 3 shows the corresponding EMF and refined SM $|S_{21}|$ responses.

Comparing the responses in Figs. 2 and 3 shows that the EMC model can very closely approximate responses obtained using the much more CPU intensive EMF model. Design using the EMF model can then be followed, if necessary, by applying the space mapping [7], or a similar technique, to further refine the EMF solution.

Yield Optimization of the Double Folded Stub

For Monte Carlo estimation we assumed a uniform distribution and 0.5 mil tolerance on all the geometrical parameters. The yield estimated from 250 statistical outcomes using the 4.8 mil

EMC model at the nominal minimax solution is 17.6 %. We carried out yield optimization using 100 outcomes. The yield is increased to 32.4 %. Fig. 4 shows the $|S_{21}|$ response from Monte Carlo simulation after yield optimization. The centered solution is listed in Table II.

Subsequently, we performed Monte Carlo analyses utilizing the 0.8 mil EMF model at the nominal and centered solutions. The specifications for these analyses are uniformly relaxed to

$$|S_{21}| > -4 \text{ dB} \quad \text{for} \quad f < 9.5 \text{ GHz and } f > 16.5 \text{ GHz}$$

$$|S_{21}| < -29 \text{ dB} \quad \text{for} \quad 12 \text{ GHz} < f < 14 \text{ GHz}.$$

Yields estimated from 250 outcomes are 18 % for the nominal and 42.5 % for the centered solutions, respectively. The more than 20 % increase in yield estimated using the EMF model confirms the effectiveness of design centering with the EMC model.

Robustness Analysis of the Nominal Solution

We investigated the robustness of EMC optimization for the double folded stub filter. The filter was optimized with L_1, L_2 and S selected as the designable parameters. W_1 and W_2 were fixed. Subsequently, we performed a number of EMC minimax optimizations, each starting from a different random starting point. We used 30 different starting points uniformly spread around the minimax solution within ±20 % deviation.

Fig. 5 plots the $|S_{21}|$ responses at all of the 30 starting points. Bars in Fig. 5(b) represent the Euclidian distances between the minimax solution and the perturbed starting points. The corresponding diagrams after the optimization are shown in Fig. 6. In Fig. 7, we visualise the optimization path taken by the minimax optimizer by indicating the starting and optimized points for each optimization. The paths are shown for different pairs of designable parameters.

We can observe that nearly all of the optimizations converged to the reference minimax solution. This shows that the optimized solution is robust and that EMC optimization provides consistent results even if started from different starting points. This study has been confirmed from other families of starting points and with other gradient optimizers.

Conclusions

We have exploited low-cost EM simulation utilizing a coarse grid for numerical field solutions. We have presented novel results involving coarse grid simulation, optimization and design centering of a double folded stub filter. Fine grid verification of the optimized solution has demonstrated that coarse grid models can provide qualitative and quantitative information about the performance of a circuit within a more practical time frame. We have studied the robustness of the coarse grid solution using the Monte Carlo method. Coarse grid EM simulation is especially attractive for structures for which analytical/empirical or theoretical circuit models are not readily obtainable.

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TABLE I

DESIGN OF THE DOUBLE FOLDED STUB FILTER

Parameter	Before Optimization	Coarse Grid Solution	SM Refined Solution
L_1 (mil)	90.00	87.27	87.33
L_2 (mil)	80.00	86.40	86.99
W_1 (mil)	4.80	5.19	5.00
W_2 (mil)	4.80	4.80	4.80
S (mil)	4.80	4.80	4.80

TABLE II

YIELD OPTIMIZATION OF THE DOUBLE FOLDED STUB FILTER

Parameter	Before Yield Optimization	After Yield Optimization
L_1 (mil)	87.27	88.58
L_2 (mil)	86.40	86.14
W_1 (mil)	5.19	5.17
W_2 (mil)	4.80	4.80
S (mil)	4.80	4.80
Coarse Grid Yield (%)	17.6	32.4
Fine Grid Yield (%)	18.0	42.5

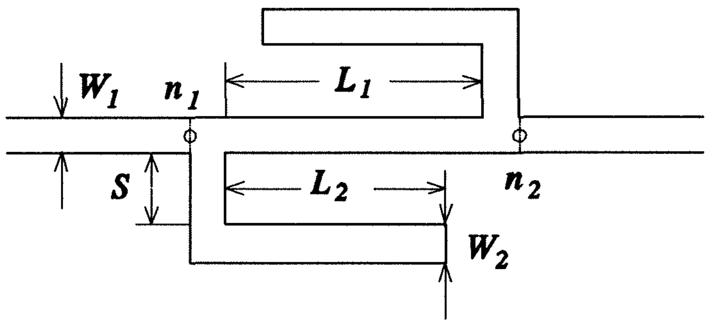


Fig. 1. Double folded stub microstrip structure for band-stop filter applications [3].

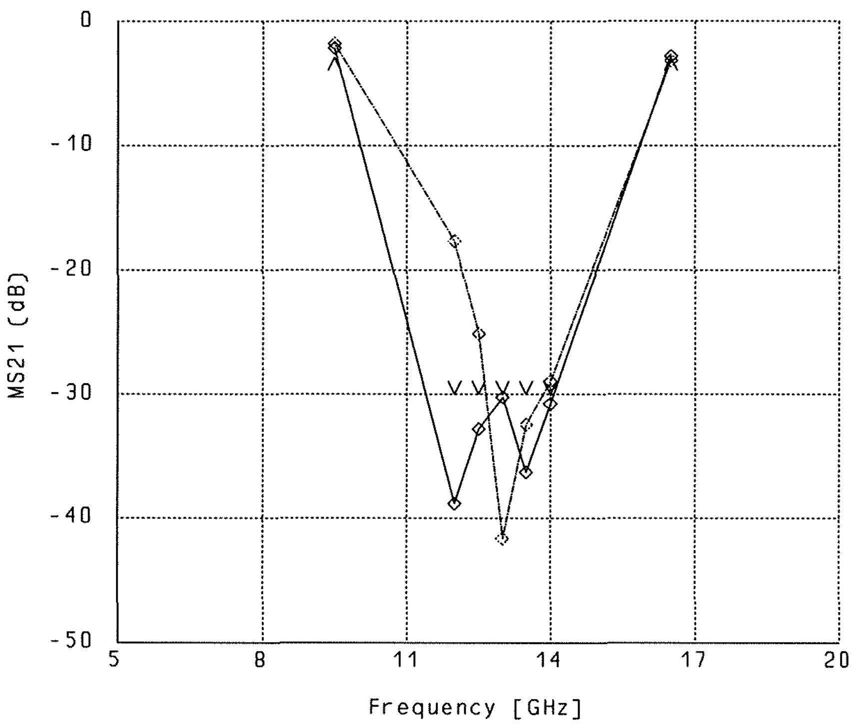
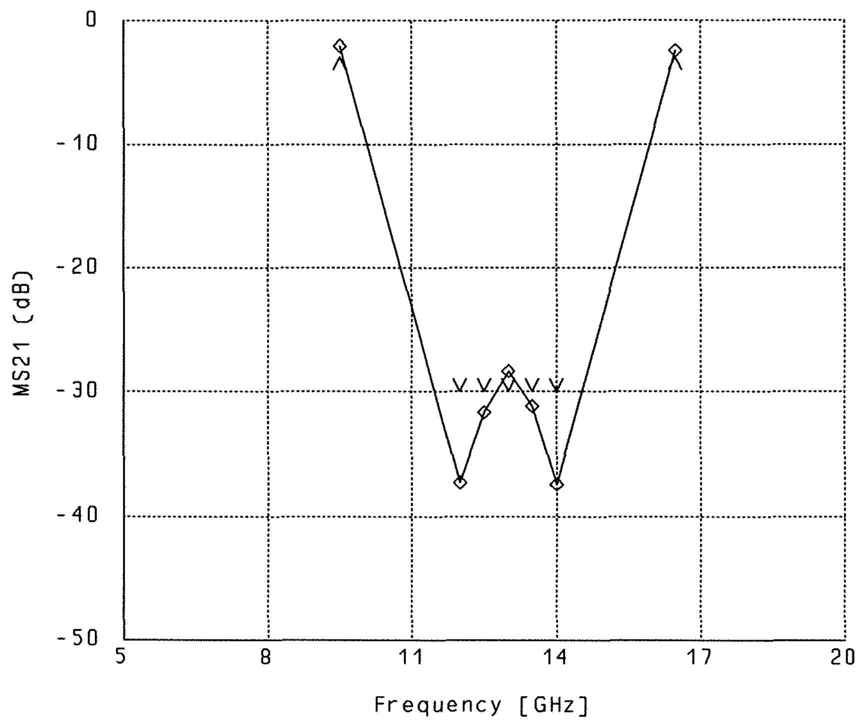
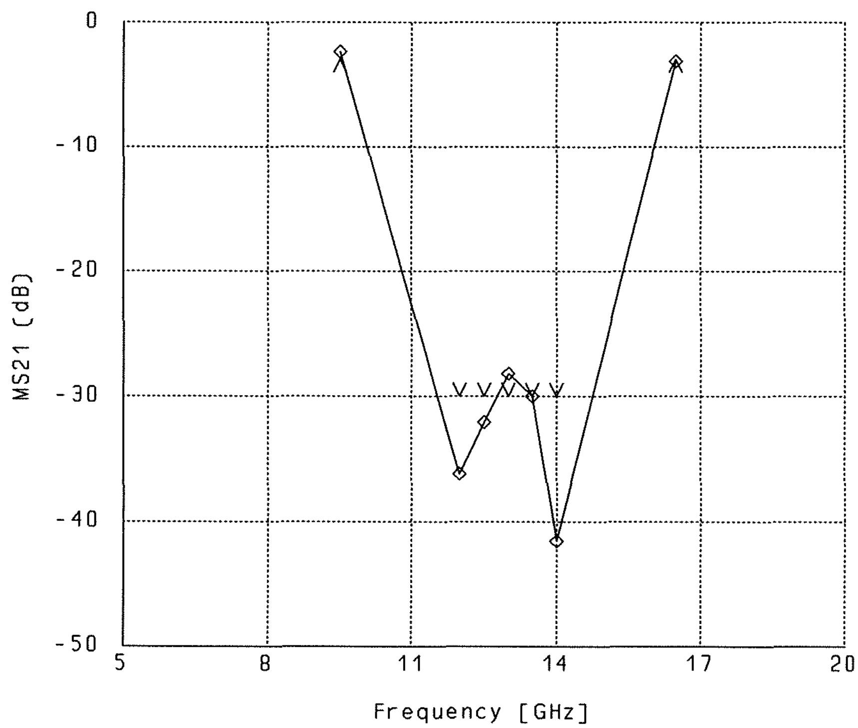


Fig. 2. EMC design of the double folded stub filter: the $|S_{21}|$ response of the filter before (dotted line) and after (solid line) minimax optimization.



(a)



(b)

Fig. 3. EMF design of the double folded stub filter: (a) shows the fine grid $|S_{21}|$ response at the minimax solution, (b) shows the $|S_{21}|$ response for SM refined solution simulated using the fine grid.

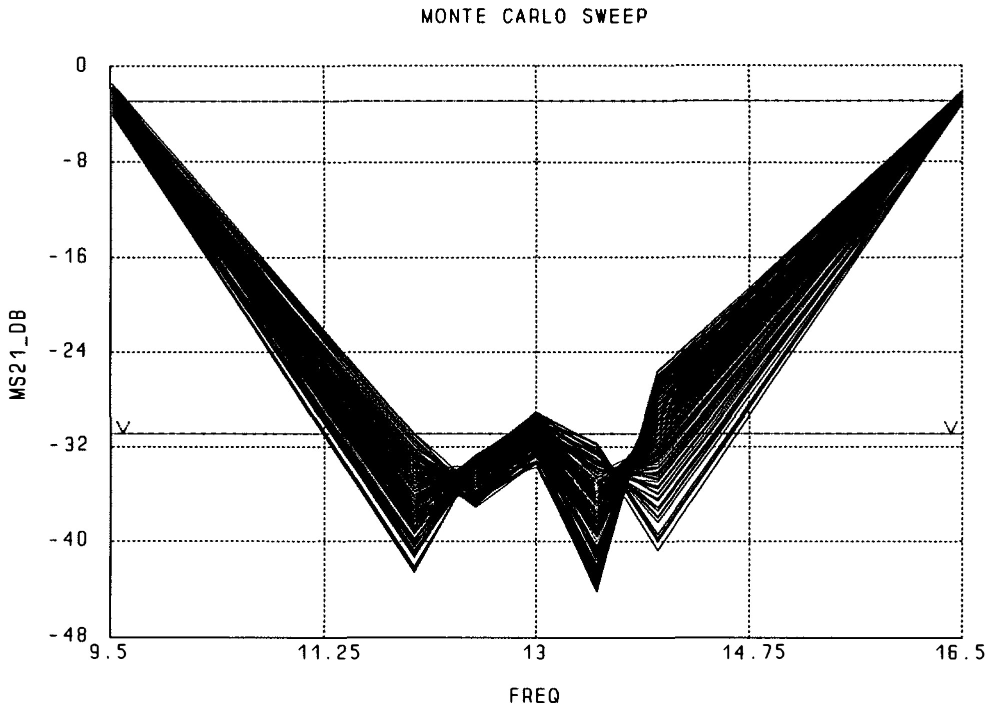
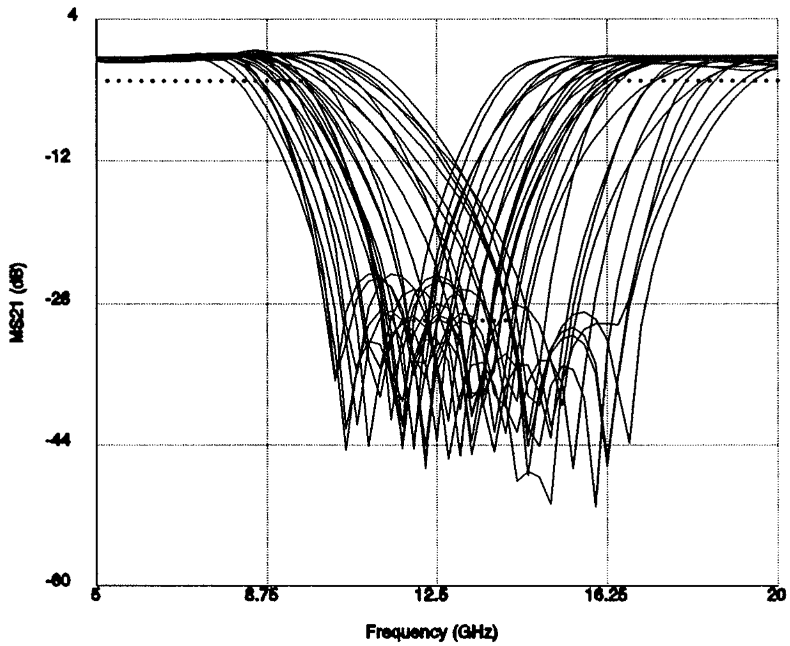
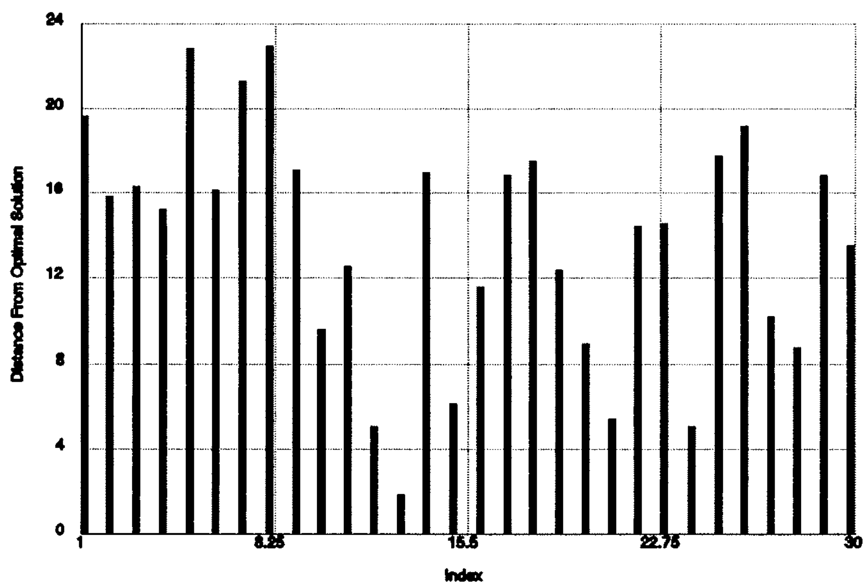


Fig. 4. The $|S_{21}|$ Monte Carlo sweep after yield optimization. 250 outcomes are used for yield estimation and 100 outcomes are used for yield optimization. We limit the number of analyzed frequencies to two in the pass-band and five in the stop-band to further decrease the time needed for analysis.

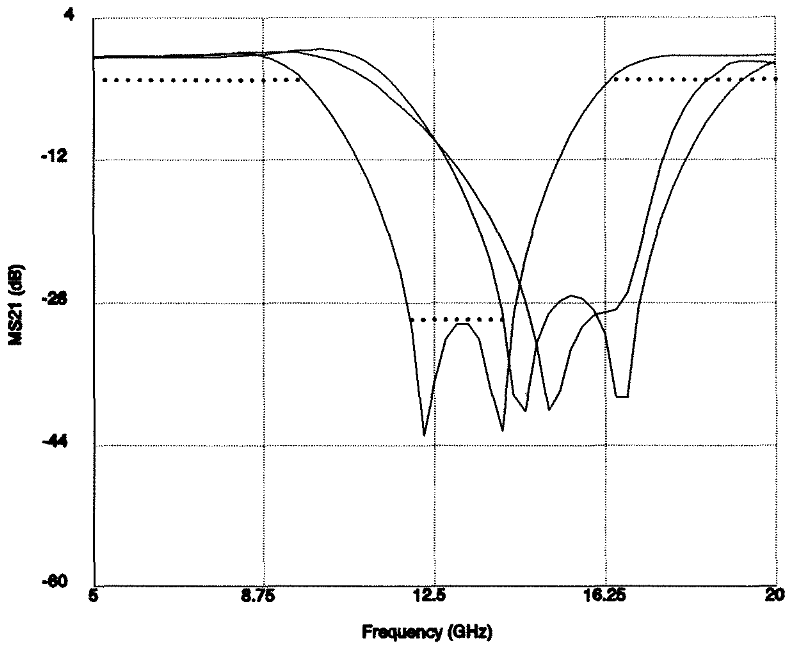


(a)

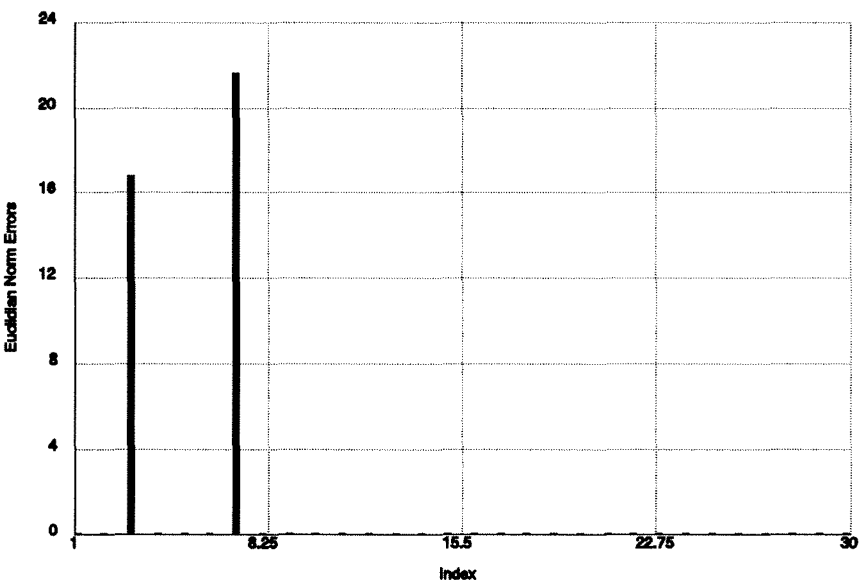


(b)

Fig. 5. (a) The simulated $|S_{21}|$ at 30 points randomly generated around the reference minimax solution, and (b) the Euclidian distances between the random points and the reference minimax solution.

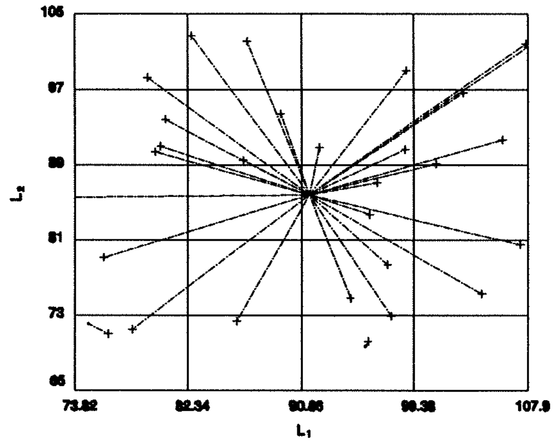


(a)

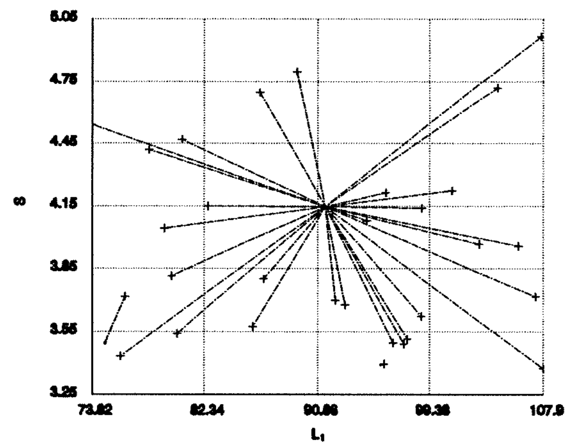


(b)

Fig. 6. (a) Simulated $|S_{21}|$ at the optimized solutions from the 30 randomly generated starting points shown in Fig. 5, (b) the Euclidian distances between the optimized points and the reference minimax solution.



(a)



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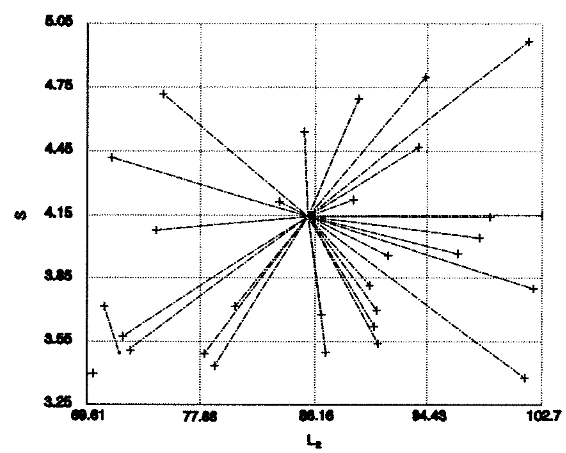

(c)

Fig. 7. Visualization of the paths taken by the minimax optimizer for each of the randomly generated starting points. We indicate the starting (+) and optimized (·) solution points for each optimization. The points are shown for different pairs of the designable parameters: (a) for L_1 and L_2, (b) for L_1 and S, and (c) for L_2 and S.