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Real-Time Amplifier Optimization Algorithm for Adaptive Radio Using a Tunable-Varactor Matching Network

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***Abstract* — Fast load impedance tuning of a varactor diode matching network to maximize amplifier gain in real-time reconfigurable circuitry is demonstrated. A published tunable varactor-diode matching topology is designed for operation at 1.3 GHz to provide significant Smith Chart coverage. A steepest-ascent algorithm is applied for fast optimization, and measurement results indicate excellent convergence from multiple starting points within the Smith Chart. Algorithm data compares well with traditional load-pull results measured with both a commercially available tuner and the tunable-varactor network, and searching with the varactor tuner search is much faster than a traditional mechanical tuner.**

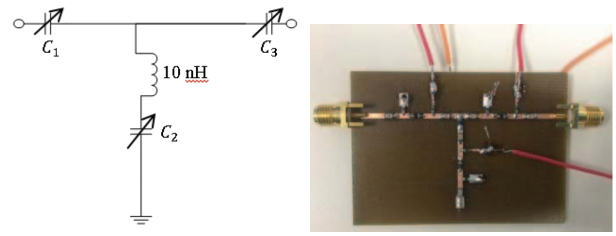
***Index Terms* — amplifiers, tunable circuitry, load-pull, nonlinear measurements, design, cognitive radio.**

I. Introduction

Reconfigurable matching circuitry is needed in cognitive and adaptive wireless transmitters for real-time changes in operating frequency and system performance requirements. We designed a 1.3 GHz matching network using the approach of Fu [1] and used this to perform fast tuning of a field-effect transistor (FET), optimizing gain using a fast steepest-ascent algorithm. Nemati has demonstrated design of varactor-based tunable matching networks for dynamic load modulation [2]. Qiao [3] and du Plessis [4] have reported real-time impedance matching using genetic algorithms, which tend to be inherently slow for many impedance matching problems. We have previously demonstrated optimization of load impedance to maximize output power [5]. This previous application of algorithms, however, is idealized in many ways. In this paper, we implement the fast load-pull search to maximize transducer gain G_T using a prototype tunable-varactor circuit for use in real-time reconfigurable transmission.

II. Tunable Matching Network Design and Challenges

We designed a tunable-varactor matching network based on the method of Fu [1] at 1.3 GHz (Fig. 1(a)). The circuit was fabricated on a 59-mil FR4 substrate (Fig. 1(b)) and characterized at 0 dBm input power using S-parameter measurements (Fig. 2). The characterized range of the tuner covers much of the Smith Chart.



(a) (b)

Fig. 1. (a) Design of 1.3 GHz tunable matching network, based on Fu [1], (b) implemented tunable-varactor matching network

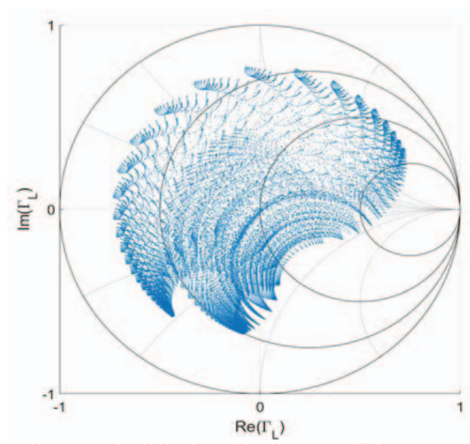


Fig. 2. Characterized load reflection coefficient states for the tunable varactor matching network

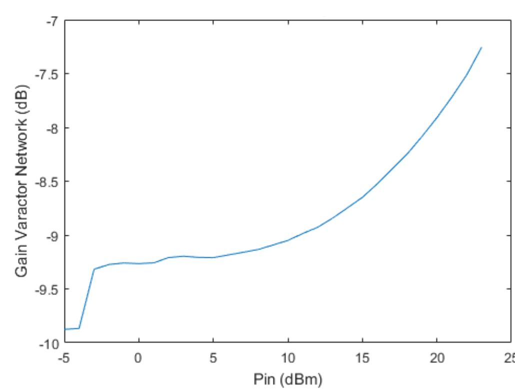


Fig. 3. Measured $|S_{21}|$ versus input power for the varactor matching network at $\Gamma_L = 0.7\underline{/90°}$.

The tuner was also tested for nonlinear behavior. Significant variations in the S-parameters with increasing input power are observed. Figure 3 shows that at $\Gamma_L = 0.7\underline{/90°}$, the matching network $|S_{21}|$ varies approximately 2.5 dB over input power variation from -5 dBm to +23 dBm. Additional testing over different varactor bias conditions for C_1, C_2, and C_3 shows that variations are most significant for large values of the varactor bias voltages. As such, accurate characterization of Γ_L is needed near the value of power expected to be input to the matching network. Because the purpose of the present paper is to demonstrate the feasibility of fast tuning using a tunable-varactor matching network, a low power value is used to avoid these nonlinearities.

III. Algorithm Adaptation for Varactor Network

Our previous gradient search optimization [5] was modified and implemented with the tunable-varactor network to maximize G_T. A plane can be fit to the G_T surface near the candidate Γ_L representing the change in G_T from the candidate as a function of $\Delta\Gamma_L = \Delta\Gamma_r + j\Delta\Gamma_i$:

$$\Delta G_T = a\Delta\Gamma_r + b\Delta\Gamma_i, \quad (1)$$

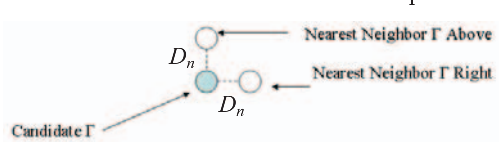
where a and b are real coefficients that must be found. It is desired (Fig. 4(a)) to estimate the gradient using measurements of G_T at the neighboring points $(D_n, 0)$ and $(0, D_n)$ with respect to the candidate Γ_L. If these are not available from the characterization, measurement should be performed at characterized nearby points $(\Delta\Gamma_{r1}, \Delta\Gamma_{i1})$ and $(\Delta\Gamma_{r2}, \Delta\Gamma_{i2})$, due to the difficulty of accurate interpolation with the varactor tuners. If ΔG_{T1} and ΔG_{T2} are the measured G_T values relative to the candidate at these points, this gives two equations,

$$\Delta G_{T1} = a\Delta\Gamma_{r1} + b\Delta\Gamma_{i1}$$
$$\Delta G_{T2} = a\Delta\Gamma_{r2} + b\Delta\Gamma_{i2}$$

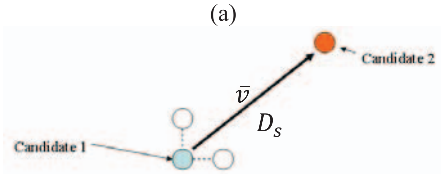
that can be solved simultaneously for a and b. The gradient of this surface ΔG_T is calculated as follows:

$$\nabla(\Delta G_T) = \hat{\Gamma}_r a + \hat{\Gamma}_i b, \quad (2)$$

and the search vector in the direction of steepest ascent is



(a)



(b)

Fig. 4. (a) Estimation of gradient by Γ_L measurements of nearby points separated by neighboring-point distance D_n. (b) Jump to the next candidate point in the direction of steepest ascent by search distance D_s (reprinted from [5] for convenience).

$$\bar{v} = \frac{D_s \nabla(\Delta G_T)}{|\nabla(\Delta G_T)|}, \quad (3)$$

as shown in Fig. 4(b). The rest of the algorithm proceeds similarly to our standard-tuner method [5]. The search distance D_s is divided by a factor of 2 if the next candidate provides a lower G_T value. The search selects the best measured point as the optimum when D_s becomes less than the prespecified resolution distance D_r.

IV. Measurement Results

The algorithm was measurement tested using a Microwave Technologies MWT-173 FET, with single-tone input power of -20 dBm at 1.3 GHz. The small input power value was used to ensure the varactor network is operated in its linear region. Custom load-pull software was implemented for matching and fixture network characterization and correction, as well as communication with instrumentation. Figure 5 shows the -20 dBm load-pull characteristics as measured by the varactor tuner, compared with contours measured by a standard Maury Microwave tuner. The optimum Γ_L and G_T values are nearly identical for the varactor and Maury tuners.

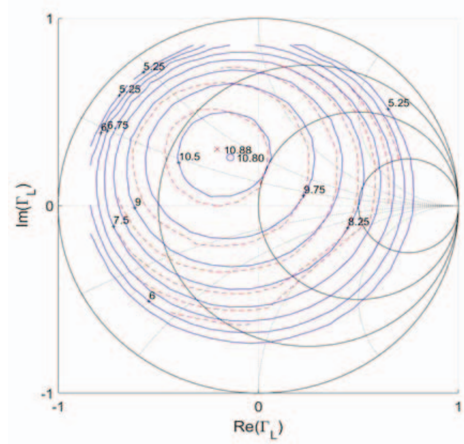


Fig. 5. 1.3 GHz single-tone MWT-173 FET load-pull transducer gain (G_T) contours measured using the tunable-varactor matching network (dashed curves, optimum G_T =10.88 dB at $\Gamma_L = 0.36\underline{/124°}$) and Maury load-pull tuner (solid curves, optimum G_T = 10.80 dB at $\Gamma_L = 0.29\underline{/118°}$) for -20 dBm input power.

Figures 6 and 7 show two algorithm searches taken from different starting values of Γ_L within the operating region of the matching network. Table I shows excellent agreement of the search end Γ_L and maximum G_T values for algorithm search results from 16 different starting Γ_L values. The results also correspond well with traditional load-pull from varactor and Maury tuners.

Even for bench-top testing with significant equipment overhead, searching with the varactor tuner is much faster than with the Maury tuner. An algorithm run from $\Gamma_L = 0$

required 1 minute, 15 seconds using the varactor tuner, compared to 5 minutes, 38 seconds using the Maury tuner.

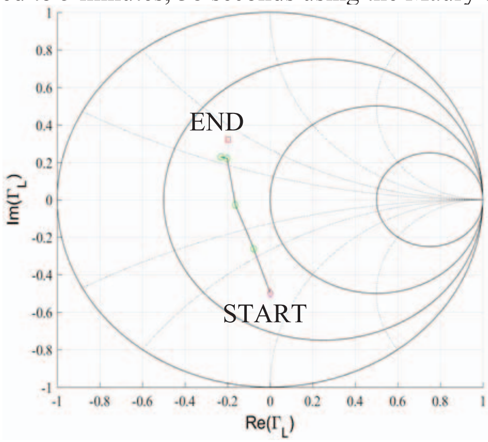


Fig. 6. Fast load-impedance optimization for output power from starting location $\Gamma_L = 0.50\underline{/-90.0^\circ}$. A maximum $G_T = 10.92$ dB was obtained at $\Gamma_L = 0.38\underline{/122^\circ}$ with 16 experimental queries.

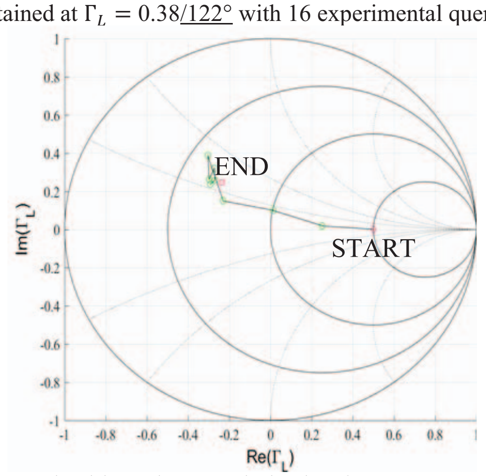


Fig. 7. Fast load-impedance optimization for output power from starting location $\Gamma_L = 0.50\underline{/0^\circ}$. A maximum $G_T = 10.87$ dB was obtained at $\Gamma_L = 0.34\underline{/134^\circ}$ with 33 experimental queries.

V. Conclusions

A fast real-time load-impedance search algorithm has been demonstrated on a tunable-varactor matching network. The tunable-varactor network provides repeatable results from multiple starting reflection coefficients with a small number of measurements, comparing well with traditional load-pull measurements, but allowing fast, real-time reconfiguration. Results show excellent correspondence for different starting load reflection coefficient values, and compare well with traditionally measured load-pull results. This algorithm is expected to be useful for implementation in cognitive communication and radar systems, allowing the matching network to quickly adapt for changing frequency bands and performance requirements. Future work will investigate advanced power-dependent characterization to counteract the effects of matching-network nonlinearities.

Acknowledgment

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Table I: Tunable-Varactor Matching Network Algorithm Results from Multiple Starting Reflection Coefficients

Start Γ_L	End Γ_L	Max. G_T(dB)	# Meas.
0	0.32/136°	10.89	14
0.25/0°	0.38/119°	10.89	17
0.25/45°	0.36/140°	10.87	18
0.25/90°	0.40/128°	10.88	19
0.25/-45°	0.37/141°	10.91	17
0.25/-90°	0.30/128°	10.92	17
0.25/135°	0.38/129°	10.89	23
0.25/180°	0.36/141°	10.90	10
0.25/-135°	0.36/129°	10.88	18
0.5/0°	0.34/133°	10.87	33
0.5/45°	0.29/129°	10.89	20
0.5/90°	0.35/137°	10.95	14
0.5/-135°	0.31/118°	10.89	20
0.5/-90°	0.38/122°	10.92	16
0.5/135°	0.38/134°	10.91	17
0.5/180°	0.39/151°	10.84	10

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