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Comparison of Bias-Voltage and Reflection-Coefficient Based Reconfiguration of a Tunable-Varactor Matching Network for Adaptive Amplifiers

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***Abstract* — For future adaptive radio and radar transmission in a dynamic spectrum access environment, the radio-frequency circuitry will be need to be reconfigurable to allow adjustment of the operating frequency and the transmission spectrum in a congested environment. A prototype tunable amplifier matching network was implemented using varactors as the tunable elements. A method in which the control bias voltages of the varactors are directly tuned is compared with a previously demonstrated algorithm that tunes based on the reflection coefficient through a nonlinear characterization of the varactor matching network. The algorithms are both designed to optimize the power-added efficiency of the amplifier while keeping the adjacent-channel power ratio below a pre-specified constraint value. Lower average time per measurement is achieved for the voltage-based search, but the total search time is lower for the reflection-coefficient based search. This comparison of algorithms is useful in developing a reconfigurable transmitter amplifier that can adapt on the fly to meet changing spectral requirements.**

***Index Terms* — reconfigurable circuitry, load-pull, algorithms, characterization methods**

I. Introduction

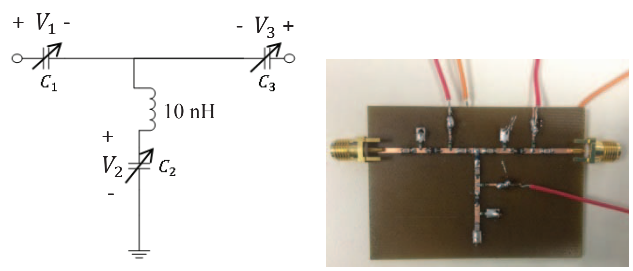
The need to share the radio spectrum among a dramatically increasing number of users has caused an increasing amount of spectrum to be allocated in real time. This will require many new communication and radar systems to be reconfigurable. Next-generation transmitter amplifiers will require tunable matching networks that can re-tune in real time, maximizing performance for changing frequency assignments and spectral mask outputs. Using the topology of Fu [1], we have designed a reconfigurable matching network for operation at 1.3 GHz [2]. An intelligent algorithm has been implemented, along with a power-dependent characterization [3], to maximize the power-added efficiency (PAE) while maintaining adjacent-channel power ratio (ACPR) below a pre-specified maximum [4].

Qiao describes a two-level optimization that is based directly on the varactor bias voltage and the settings of micro-electrical mechanical systems (MEMS) switches, including a genetic algorithm in the optimization [5]. Du Plessis presents a CAD-based algorithm that uses a genetic algorithm to tune matching-circuit component values as the optimization parameters, but confesses that the genetic algorithm is inherently slower than many other options [6].

The present paper compares optimization using direct tuning of varactor-bias control voltages with optimization using tuning of the load reflection coefficient. Measurement test results are presented, and advantages and disadvantages observed in each approach are discussed.

II. Algorithm Description

Figure 1 shows the matching network circuit and topology for the design [2]. The matching network consists of three varactors in a tee configuration. The shunt varactor is placed in series with a 10 nH inductor. As such, the three varactor capacitances C_1, C_2, and C_3 are controlled by variable voltages V_1, V_2, and V_3, respectively.



(a) (b)

Fig. 1. (a) Design of 1.3 GHz tunable matching network, based on Fu [1], (b) implemented tunable-varactor matching network. Reprinted from [2] for convenience.

A block diagram of the test setup is shown in Fig. 2. A Microwave Technologies MWT-173 field-effect transistor (FET) was used as the transistor under test. MATLAB was used to control the measurement instrumentation, consisting of a Keysight Technologies signal generator, power meter, and spectrum analyzer. S-parameter characterizations of the fixtures and (where applicable) the tunable-varactor network were stored in MATLAB and used for calibrations and reference-plane corrections.

The first approach, which allows use of our previously demonstrated traditional load-pull algorithms [6], performs tuning based on the value of the load reflection coefficient Γ_L. The reflection-coefficient search requires a characterization mapping values of Γ_L to combinations of the varactor bias voltages V_1, V_2, and V_3. Because the tunable-varactor matching network behavior is significantly dependent on its

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input power, a power-dependent characterization is necessary to accurately describe the value of Γ_L presented to the amplifier at power values in the tuner's nonlinear region [3]. To perform the characterization, the value of Γ_L was measured using a vector network analyzer at multiple combinations across the ranges of the three varactor bias voltages V_1, V_2, and V_3 at different input power levels. Using Γ_L as a complex input parameter, a modified gradient-based tuning search was performed to maximize PAE while meeting ACPR constraints, as described by Rezayat [3]. The reference plane for power and PAE measurements is after the tunable-varactor matching network (Fig. 2). This is different from a traditional load-pull measurement, where the reference plane is typically between the transistor and tunable-varactor. Moving the reference plane to the output of the tunable-varactor network, however, is much more useful in a real-time system where the matching network possesses any amount of loss (especially if the loss is bias dependent, as in this case).

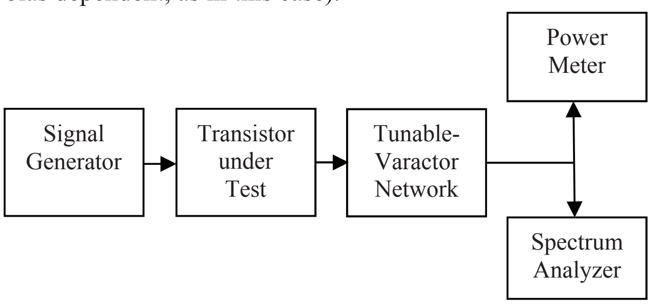

Fig. 2. Measurement test setup block diagram

Figure 3 shows a diagram of the optimization approach used for the reflection-coefficient search. Search vectors are constructed based on unit vectors in the optimum PAE direction ($\hat{p}$) (direction of the PAE gradient) and optimum ACPR direction ($\hat{a}$) (direction opposite to the ACPR gradient). The unit vector $\hat{b}$ bisects $\hat{p}$ and $\hat{a}$. If the ACPR at Candidate 1 is out of compliance (greater than the pre-specified ACPR limit), the search vector from Candidate 1 to the next candidate (Candidate 2) in the gradient search is defined as follows [6]:

$$\bar{v} = \hat{a}D_a + \hat{b}D_b, \tag{1}$$

where

$$D_a = \frac{D_s}{2}\frac{|ACPR_{meas} - ACPR_{target}|}{|ACPR_{worst} - ACPR_{target}|} \tag{2}$$

and

$$D_b = \frac{D_s}{2}\frac{|\theta_{meas} - \theta_{target}|}{\theta_{target}}. \tag{3}$$

D_s is a search-distance parameter pre-selected by the user. $ACPR_{meas}$ is the measured value of ACPR at the present candidate. $ACPR_{target}$ is the limiting value of ACPR. $ACPR_{worst}$ is the value of ACPR measured to this point in the search that is farthest from $ACPR_{target}$. If θ is defined as the angle between $\hat{a}$ and $\hat{b}$, then the desired value of θ is $\theta_{target} = 90$ degrees for a Pareto-optimum solution between PAE and ACPR. θ_{meas} is the measured value of θ at the present candidate [4].

If the ACPR value at Candidate 1 is in compliance (less than the pre-specified ACPR limit), then the search vector is instead defined [4] as

$$\bar{v} = \hat{p}D_a + \hat{b}D_b, \tag{4}$$

as shown in Fig. 3(c).

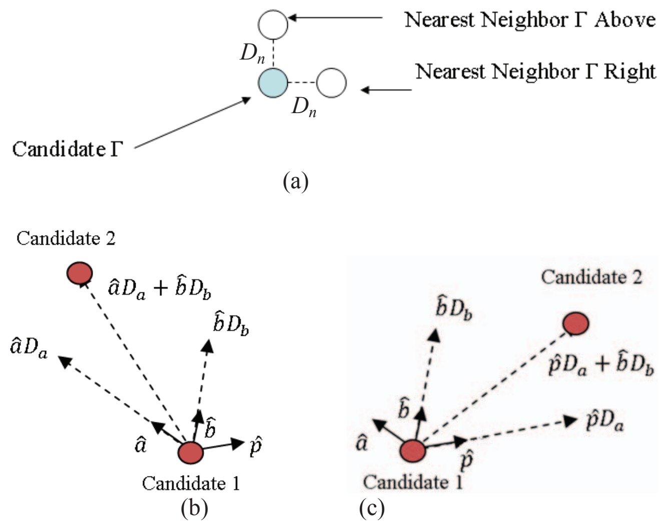

Fig. 3. Process for determining the next candidate point in the reflection-coefficient based search: (a) PAE and ACPR gradient estimation, (b) finding the next candidate using the gradient estimation if the ACPR at Candidate 1 is greater than the defined limit (out of compliance), (c) finding the next candidate using the gradient estimation if the ACPR at Candidate 1 is less than the defined limit (in compliance). Reprinted from [4] for convenience.

An alternative method is the direct tuning of the varactor bias voltages. A significant benefit of this approach is that no characterization is required; the tuning is performed empirically based on the measured values of PAE and ACPR at the output of the tuner. A three-dimensional modified gradient approach is applied to the three varactor control voltages V_1, V_2, and V_3.

The bias-voltage search uses the same gradient estimation and vector construction as in the reflection-coefficient search of Fig. 3, except in three dimensions, corresponding to the control-voltage parameters V_1, V_2, and V_3. Figure 4 shows the gradient estimation approach used for the varactor-voltage based tuning. In the case of a network with three tuning elements, the reflection-coefficient based search is performed in a two-dimensional search space, while the control-voltage based search is performed in a three-dimensional search space. The construction of the search vectors is identical to Fig. 3(b) and (c) and uses the same equations (1) through (4), except they are applied in the three-dimensional (V_1, V_2, V_3) space.

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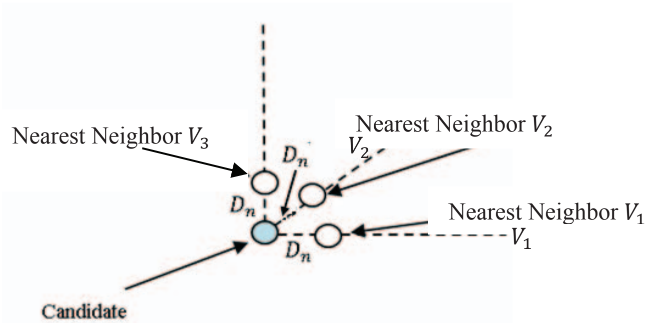

Fig. 4. Process for determining the gradient in the control-voltage based search. The search vector construction is the same as pictured in Fig. 3(b) and (c), except this vector construction is carried out in the (V_1, V_2, V_3) space instead of the complex Γ_L plane.

III. Reflection-Coefficient Search

The two different optimizations were compared based on their performance in matching a Microwave Technologies MWT-173 FET. The device operated at a bias of V_{GS} = -1.5 V, V_{DS} = 3 V with input power P_{in} = 4 dBm.

For both the reflection-coefficient and bias-voltage searches, ACPR ≤ -30.5 dBc was used as the ACPR constraint. In order to tune the load reflection coefficient of the matching network in the optimization, a characterization is needed relating the bias voltages of the varactors to the load reflection coefficient. Since interpolation between characterized states is not feasible [2], the characterization must be extensive. The optimization will only be able to select points for which a characterized state has been measured. The characterized load reflection coefficient states for the tunable matching network used are shown in Figure 5.

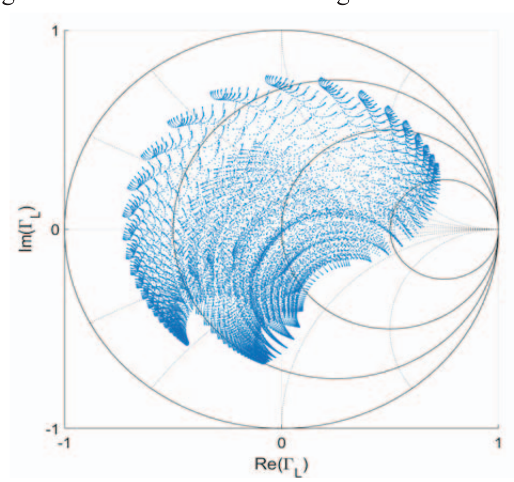

Fig. 5. Characterized load reflection coefficient states for the tunable varactor matching network

Figure 6 shows the traditionally measured PAE and ACPR load-pull contours for the MWT-173 FET taken with the reference plane at the output of the tunable-varactor matching network. Because the loss of the tunable-varactor matching network varies significantly across the Smith Chart, non-convex contours are obtained for this reference plane, even though PAE contours taken at the reference plane between the transistor and tuner would be convex. The reflection-coefficient search endpoints of the fast search iterations are plotted with the contours in Fig. 6 for comparison, and most of the search endpoints compare well with the constrained optimum calculated from the traditional load-pull data.

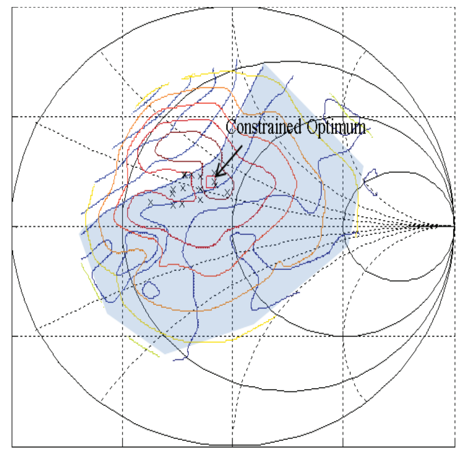

Fig. 6. Search end locations plotted with PAE and ACPR contours. The PAE contours are shown in different hues of red and yellow, with the ACPR contours shown in blue. The acceptable ACPR region (ACPR ≤ -30.5 dBc) is shaded. The constrained optimum, as taken from traditional load-pull data, is shown as a red square. The optima found through reflection-coefficient searches are each labeled with an 'x'.

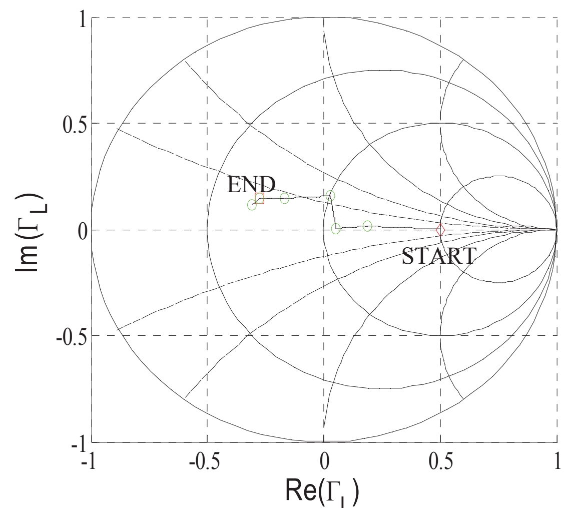

Fig. 7. Reflection-coefficient search results for starting point Γ_L = 0.50/0°. The constrained optimum was found at Γ_L = 0.31/152°, providing PAE = 27.73% and ACPR = -30.6 dBc. 26 measurements were required, with an average time per measurement of 3.63 seconds.

Fig. 7 shows the trajectory of a reflection-coefficient search starting from Γ_L = 0.50/0.00°. Table I shows the reflection-coefficient search results from 16 different Γ_L values. It can be seen that the end PAE values are reasonably similar for many of the starting points, and the number of measurements

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required for the searches ranges from 11 to 34. All results possess ACPR values close to the limiting value of -30.5 dBc.

TABLE I: RESULTS OF REFLECTION-COEFFICIENT SEARCH FROM MULTIPLE STARTING POINTS

Start Γ_L	Start PAE (%)	End Γ_L	End ACPR (dBc)	End PAE (%)	# Meas	Avg. time per meas. (sec.)
0	21.24	0.19/139°	-31.0	26.87	11	3.41
0.25/0°	13.79	0.28/143°	-30.8	28.40	21	3.39
0.25/45°	20.10	0.33/133°	-30.6	29.31	23	3.39
0.25/90°	22.74	0.39/164°	-30.5	25.61	12	3.43
0.25/-45°	12.40	0.25/110°	-31.4	27.67	21	3.50
0.25/-90°	12.39	0.32/148°	-31.1	27.68	34	3.41
0.25/135°	26.76	0.22/112°	-31.0	27.10	16	3.54
0.25/180°	23.80	0.29/160°	-31.6	26.85	13	3.39
0.25/-135°	16.61	0.22/131°	-30.8	26.71	14	4.28
0.5/0°	6.94	0.31/152°	-30.6	27.73	26	3.63
0.5/45°	8.28	0.21/112°	-31.4	26.31	30	3.40
0.5/90°	12.79	0.27/122°	-30.9	28.47	27	3.48
0.5/-135°	9.22	0.25/156°	-31.1	25.69	24	3.42
0.5/-90°	5.27	0.16/98°	-31.8	24.53	20	3.40
0.5/135°	22.18	0.30129°	-30.6	28.91	17	3.53
0.5/180°	9.91	0.32/132°	-30.5	28.95	29	3.48

IV. BIAS-VOLTAGE SEARCH

Finding the constrained optimum PAE by directly tuning the varactor bias voltages requires less overhead complexity than the reflection-coefficient tuning. No characterization mapping varactor bias voltages to reflection coefficients is needed, and the search is not limited to selecting only discrete characterized states. Computation time is reduced, because there is no need to search through a table of values. However, since the search now occurs in a 3-dimensional space, an increased number of measurements is needed to find the optimum. Each gradient estimation requires three, instead of two, measured points in the three-dimensional search space.

Figure 8 shows the search trajectory for a bias-voltage search in the three-dimensional (V_1, V_2, V_3) space starting from $V_1 = 22$ V, $V_2 = 22$ V, and $V_3 = 22$ V. The results of the bias-voltage searches from several different starting voltage combinations are shown in Table II. For the bias-voltage search, the same settings were used as for the reflection-coefficient search previously described, with the ACPR constraint again defined as -31.5 dBc.

Figure 9 depicts all of the endpoints found using the bias-voltage search. Also plotted in Fig. 9 is a constant-PAE surface representing the (V_1, V_2, V_3) combinations providing PAE = 20%. This plot indicates that the PAE characteristic in the (V_1, V_2, V_3) voltage space is multi-modal. Each search tends toward one of two different clusters of endpoints. This occurs since for several load reflection coefficient states there is more than one varactor bias voltage combination that maps to a single load reflection coefficient. There will be more than one optimum combination of bias voltages, but the same PAE performance will be obtained because the resulting Γ_L values should be nearly identical.

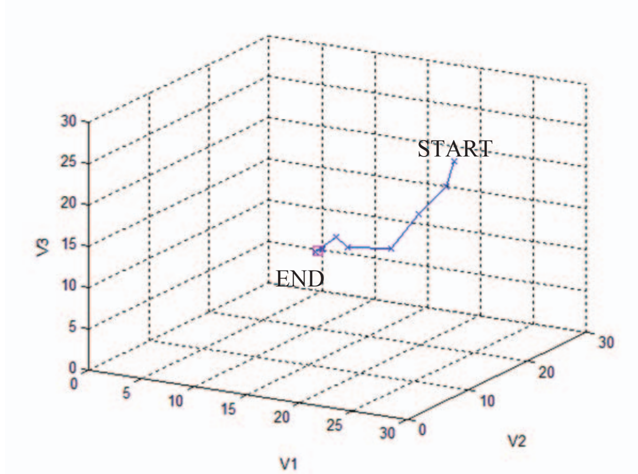

Fig. 8. Bias voltage search results for starting point $V_1 = 22$ V, $V_2 = 22$ V, $V_3 = 22$ V. The constrained optimum was found at $V_1 = 12.11$ V, $V_2 = 16.80$ V, $V_3 = 10.93$ V, providing PAE = 26.02% and ACPR = -30.97 dBc. 32 measurements were required, with an average time per measurement of 2.58 seconds.

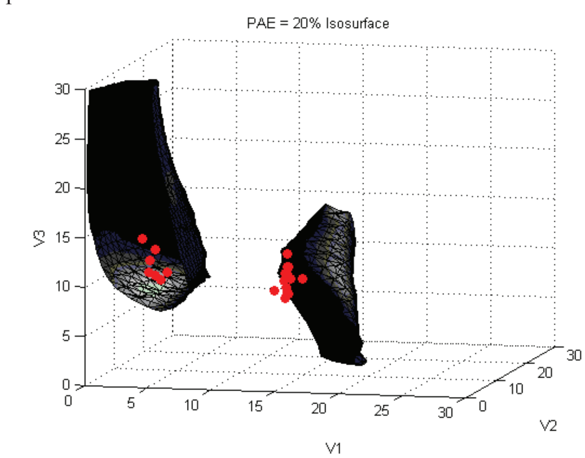

Fig. 9. End points for the control-voltage search in the (V_1, V_2, V_3) plane (red dots) shown with the equal-PAE surfaces for PAE = 20% (black)

The average results of the reflection-coefficient and bias-voltage searches are compared in Table III. The average end PAE and ACPR values compare well between the two search types. The average number of measurements is much lower for the reflection-coefficient search, but the time per measurement is much lower for the bias-voltage search. Because no characterization look-up is required, using bias voltage as the tuning parameter reduces the overhead time per measurement. However, the reflection-coefficient search uses fewer measurements, at least in part due to the difference in dimensions. The average total time per algorithm run is approximately 15 seconds slower for the bias-voltage search (89 seconds) than for the reflection-coefficient search (74 seconds). If a reconfigurable circuit is designed such that only

TABLE II: RESULTS OF BIAS-VOLTAGE SEARCH FROM MULTIPLE STARTING POINTS

Start V_1 (V)	Start V_2 (V)	Start V_3 (V)	Final V_1 (V)	Final V_2 (V)	Final V_3 (V)	End PAE (%)	End ACPR (dBc)	# Meas	Avg. time per meas. (sec)
1	1	1	5.14	1.70	13.68	28.35	-31.11	16	2.46
2	2	2	5.52	0.11	11.34	27.99	-31.26	29	2.47
3	3	3	5.78	2.98	11.20	27.04	-31.36	20	2.52
4	4	4	4.79	1.55	12.60	28.55	-31.01	25	2.46
5	5	5	5.75	1.01	10.74	27.93	-31.46	25	2.53
6	6	6	4.57	0.00	15.07	29.63	-30.53	19	2.46
7	7	7	5.06	0.18	11.66	28.14	-31.06	52	2.50
8	8	8	5.34	0.64	13.89	27.23	-31.11	34	2.48
9	9	9	12.53	14.10	6.98	26.94	-30.53	25	2.49
10	10	10	12.65	14.73	7.26	26.95	-30.80	29	2.50
11	11	11	12.34	15.74	9.01	26.46	-30.59	40	2.50
12	12	12	12.09	15.62	8.45	26.90	-30.52	33	2.49
13	13	13	12.23	16.05	9.76	26.98	-30.75	81	2.46
14	14	14	12.65	15.55	8.63	26.63	-30.98	53	2.47
15	15	15	11.52	14.68	7.60	26.60	-30.91	25	2.47
16	16	16	12.36	15.30	7.78	26.93	-30.54	53	2.47
17	17	17	13.54	15.69	8.64	25.85	-30.84	16	2.47
18	18	18	12.28	16.23	9.70	26.02	-30.79	41	2.46

TABLE III: COMPARISON OF BIAS-VOLTAGE AND REFLECTION-COEFFICIENT SEARCH RESULTS

		End ACPR (dBc)	End PAE (%)	Avg. # Meas	Avg. Time per Meas. (sec)	Avg. Time per Search (sec)
Γ_L Search	Average	-30.99	27.30	21.13	3.50	73.70
	Standard Deviation	0.39	1.31	6.73	0.21	22.65
Voltage Search	Average	-30.88	27.22	35.85	2.48	88.97
	Standard Deviation	0.27	0.96	17.81	0.03	43.77

two tuning parameters exist (the same number of parameters as in the reflection coefficient search), it is likely that the bias-voltage search may be faster due to reduced computational overhead time obtainable with no characterization.

While the optimization times of both searches are over one minute in duration for the present measurement setup, it should be noted that this work is in a preliminary development stage, using a test bench setup controlled through GPIB and other software programs with significant equipment control overhead. At this preliminary stage, it is important to explore fast search methods and compare results. Future real-time implementation is expected to drastically reduce overhead for input-output and communication, allowing the reconfiguration to occur in a feasible amount of time for adaptive systems.

V. CONCLUSIONS

A varactor bias-voltage tuning optimization algorithm is compared to a traditional reflection-coefficient based optimization for a tunable-varactor load matching network in preliminary testing for future reconfigurable power-amplifier application. The bias-voltage search does not require a characterization, allowing each measurement to be performed without the use of a look-up table, saving time. However, the increased dimensionality of the bias-voltage search space results in more measurements for the searches. Even though the PAE characteristic is multi-modal in the voltage space, optimum PAE and ACPR are comparable for both searches. This preliminary investigation will be useful in the development of algorithms for much faster, future adaptive field-deployable systems.

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