Dynamic Online Learning Applied to Fast Switched-Stub Impedance Tuner for Frequency and Load Impedance Agility in Radar Applications

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***Abstract*—Switched-stub tuner topologies show promise for use in real-time tuning of high-power amplifiers in radar transmitter arrays. High-power switches can be used to expose or remove different tuning stubs from a series line in real time to adjust power-amplifier load impedance following changes in operating frequency or array scan angle. Dynamic online learning can be applied to enhance optimization of the amplifiers by updating models for tuner performance in real-time. This minimizes experimental queries needed to re-optimize on the fly as the system adjusts its operating frequency or scan angle. Measurement results are presented to optimize a six-stub tuner in a 2-4 GHz window with varying antenna impedances from a software-defined radio platform. Results show significant time savings can be achieved by applying dynamic learning.**

***Index Terms*—Power amplifiers, radar, phased arrays, reconfigurable circuits, spectrum sharing**

I. INTRODUCTION

As spectrum usage by wireless communications has grown even further with the advent of fifth-generation (5G) wireless technology, even heavier demands are being placed on radar systems to proactively share spectrum with communications in real time. Adaptive matching of the transmitter power amplifier is important to maintain high range and power efficiency through changes in operating frequency and array scan angle [1]. High-power tuning technologies have been recently developed using mechanical tuning of resonant-cavity discs [2]. While reconfiguring mechanically tuned devices can require time frames much longer than a typical radar pulse repetition interval (PRI) or coherent processing interval (CPI), new high-power electrical switch technologies are under development [3]. These switches can be used to create switched-stub impedance tuners, permitting tuning of the amplifier around the Smith Chart by changing the tuning stubs that are exposed to the main feedline through switching. The fast optimization of a switched-stub tuner in less than 35 μs is demonstrated in a recent conference paper [4]. The search technique investigates the disposition of each switch one at a time, and concludes when a complete loop of all switches has been performed with no improvement to the output power. The optimization was performed using a software-defined radio platform. Dockendorf demonstrates the use of a look-up table to decrease optimization time in a continuously optimizable evanescent-mode cavity tuner [5].

In the present paper, we introduce dynamic learning to reduce the number of measurement iterations for re-optimization of power-amplifier load impedance as the search progresses.

II. EXPERIMENTAL GOALS

In order to demonstrate the flexibility of the switched-stub tuner in changing operating conditions, experiments were performed in a scenario where both system frequency and reflection coefficient presented to the tuner vary. The change in frequency alters the maximum load impedance, which, when presented to the amplifier, leads to maximum power output. The frequencies used in this experiment, like in [4], are 2, 2.5, 3, 3.5, and 4GHz, covering an octave. The change in reflection coefficient presented by the antenna to the tuner represents a system where an antenna array is electrically scanned to another angle, resulting in changes in mutual coupling and apparent antenna reflection coefficient. The "antenna" reflection coefficients used in this experiment are Γ_{ant} = 0, $0.5\underline{/45^\circ}$, $0.3\underline{/120^\circ}$, $0.65\underline{/240^\circ}$, and $0.4\underline{/310^\circ}$. These values were chosen in order to demonstrate the robustness of the tuner in varying operating conditions, as each of the four Smith Chart quadrants are included. Fig. 1 shows a visual of these five reflection coefficients on the Smith Chart.

Previously in [4], switched-stub tuner optimization searches were performed at various operating conditions, and the system had no knowledge of these operating conditions to aid the search. In that case, each search began at the starting point with all switches open (no stubs exposed in the matching network). The searches would complete in the order of tens of microseconds, but there is room for improvement: dynamic online learning for starting point optimization. Five frequencies and five reflection coefficients provide 25 unique operating

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conditions for the system, and all switches being left open to start is not optimal at many of these conditions.

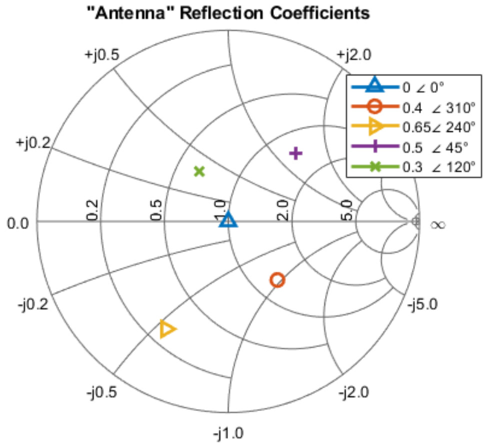

Fig. 1. Emulated antenna reflection coefficient values Γ_{ant} presented to the impedance tuner

In this experiment, the search demonstrated in [4] was used for real-time optimization of the switched-stub impedance tuner, also described and demonstrated in [4]. Searches were performed in a random order, dynamically populating the system memory with the switched-stub tuner state at which each search converged. To decrease search time, this state is used as the starting point the next time that the same operating frequency and antenna reflection coefficient (corresponding to array scan angle) are used. The hope is that, unlike in [5] where a continuous, mechanical impedance tuner is used, the previous optimal switched-stub state is also very likely to be the optimum for the next search at the same operating conditions, as the discrete impedance tuner demonstrated in [4] can only tune to 64 different states. Variations in the optimum would likely be due to different mutual coupling scenarios potentially arising from different operating environments if the platform is moving. If a system like this were to be deployed in a real-life scenario, the antenna reflection coefficients would likely not be known. However, storing the scan angle can provide an equivalent capability to storing the antenna reflection coefficient.

III. MEASUREMENT RESULTS

To test this approach experimentally, optimization searches were conducted using an Ettus X310 software-defined radio (SDR) in conjunction with a host computer. The SDR acts as the (calibrated) transmitter, power meter, and tuner switch controller in the system. Additionally, the search algorithm is stored on the SDR's FPGA for speed purposes. The host computer is used to initiate the searches, as well as to dynamically learn and recall the optimal starting points for each system operating condition. Fig. 2 shows the measurement bench.

As seen in Fig. 2, the switched-stub impedance tuner (D) is between the MWT-173 field-effect transistor (FET) (C, which serves as the device under testing (DUT)) and the Maury Microwave mechanical impedance tuner (A, which simulates the antenna reflection coefficients). The DC power supplies are used both to bias the FET and provide power to the six switches on the tuner.

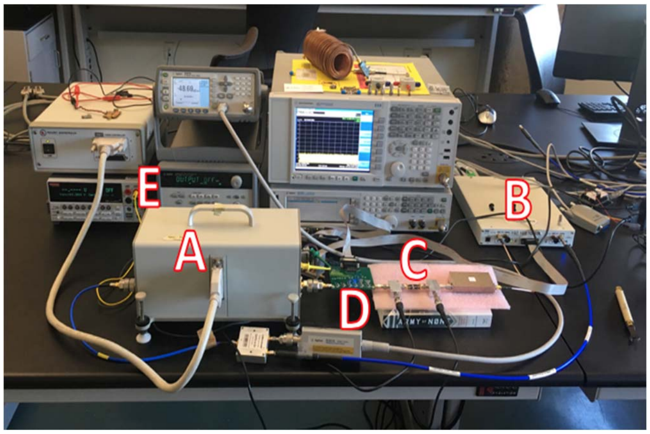

Fig. 2. Measurement setup: A – Maury Microwave tuner (presenting an "antenna" load impedance to the system), B– Ettus X310 software defined radio, C – power amplifier, D– switched-stub impedance tuner/matching network, E– bias supplies for tuner and amplifier

The results for one of the 25 optimization searches using the search of [4] without system memory is shown in Table I, below. The searched was performed with a 3.5 GHz operating frequency and an emulated antenna reflection coefficient of $\Gamma_{ant} = 0.4\underline{/310^\circ}$. The tuner states are comprised of the six-bit binary sequence representing the states of the six switches from input to output of the tuner, where 1 indicates a switch is closed and 0 indicates a switch is open. The decimal version of this number is shown as the "Tuner State" in Table I.

Highlighted in Table I is state 60, where the search converged. With dynamic learning, the system remembers this state, and the point is used as the starting point when the same system operating frequency and antenna reflection coefficient are used again.

In contrast with the Table I standard search of [4], the results for a search that utilizes dynamic learning for the same operating conditions are shown in Table II. The search converged to state 60 once again. This time, however, state 60 was the starting point, so the search only performed 7 measurements instead of 14, based on the search procedure of [4]. While the improvement from utilizing dynamic learning varies across operating frequency and antenna reflection coefficient, this example demonstrates the impact of utilizing results from previous searches with the stub tuner.

TABLE I
Search Trajectory Without Dynamic Learning

Tuner State	Output Power (dBm)	Time Taken (µs)
0	12.73	1.870
32	16.00	3.745
48	20.56	5.625
56	19.79	7.505
52	22.23	9.385
54	20.51	11.265
53	19.54	13.145
20	20.18	15.025
36	16.05	16.905
60	22.34	18.785
62	19.45	20.670
61	21.11	22.550
28	19.18	24.430
44	16.36	26.310

TABLE II
Search Trajectory With Dynamic Learning

Tuner State	**Output Power (dBm)**	**Time Taken (µs)**
60	22.26503089	1.870
28	19.12822397	3.745
44	16.40828251	5.625
52	22.23755594	7.505
56	19.83182096	9.385
62	19.46865909	11.265
61	21.11595743	13.145

To compare broader results of using dynamic learning, 25 searches without dynamic learning and 25 searches with dynamic learning were performed, and the search results were compared. A summary of notable results from the experiment are shown in Table III. Comparing the two sets of data, the most noteworthy difference is the decrease in measurement number and time taken for the searches with dynamic learning. By using dynamic learning, the average search time improved from 17.8 µs to 13.1 µs. This 26% improvement in search time is because the searches using the previous optima as starting points averaged approximately 2 fewer measurements per search. Also, as seen in the table, 80% of the searches which utilized dynamic learning converged at their starting points (the previous optimum), indicating that, in the vast majority of cases, re-performance of the search may not even be necessary if time does not allow. Of the 20% which did not end at their starting state, the output power of each starting point was within 0.13 dBm of the eventually selected optimal state, with 3/5 of the 20% being within 0.07 dBm, a difference likely attributable to measurement noise. An important consequence of this result is that if the search converges to the same optimum each time at each set of operating conditions, after an initial search to learn the optimum, searches may no longer need to be performed. It should be noted that these times only include the time for the searches to be performed, which occur solely on the FPGA. Time for the system frequency to change, time for the Maury Microwave tuner to change the emulated antenna reflection coefficient, and time for the host computer to communicate items such as starting point, transmit power level, and operating frequency to the SDR were not considered.

IV. Plans For Future Development

As noted previously, the test setup used for these experiments uses the host computer to store the system memory. In a deployed system, the system memory would need to be stored either on the FPGA itself or on a more easily deployable small-board computer, and the communication time required to retrieve the starting tuner state will need to be considered. The dynamic learning approach should be integrated into the deployable system and re-evaluated for time savings, based on the communication overhead.

TABLE III
Search Statistics from 25 Searches with Dynamic Learning and 25 Searches Without Dynamic Learning

Average Search Completion Time Without Dynamic Learning	17.8 µs
Average Search Completion Time With Dynamic Learning	13.1 µs
Average Number of Measurements Without Dynamic Learning	9.48
Average Number of Measurements With Dynamic Learning	7.2
Percentage of Repeat Optimal States	80%
Percent Time Savings	26%

V. Conclusions

Experiments have demonstrated a time savings from using dynamic learning to select an impedance tuner starting state for real-time tuning when changing operating frequency or antenna impedance, which is related to array scan angle. This has significant applications to real-time radar transmitter frequency agility, allowing maximum transmission range to be maintained in a spectrum-sharing scenario. Measurement results show that using the previous search optimum as the starting location for optimizing the switched-stub tuner can decrease the search time by up to 25 percent. As transmitters change frequency and scan angle strive to avoid interference and maintain compatibility, improved speed in optimizing the impedance tuner for optimal range can be achieved. For example, an impedance tuning optimization search may, in many cases, be performed within the timeframe of one PRI or CPI. This allows radar transmitters to quickly optimize range at new operating conditions while avoiding spectral or spatial interference with or from other wireless devices.

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