Closed-loop Adaptive Control Techniques for Matching Networks in the Uplink Mode

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***Abstract*—This paper presents a closed-loop control system for tuning the antenna matching network using power measurements in the transmit mode. Three methods are proposed as the basis of the control system to improve the efficiency of signal transmission via adaptively adjusting the scattering parameters of the matching network in real-time. The proposed adaptive match system is analyzed thoroughly using an in-house prototype comprising a parallel-LC network with two tunable capacitors. Detailed complexity analyses of the proposed methods are also presented.**

***Keywords*— adaptive match, impedance matching, , tunable network**

I. INTRODUCTION

The ever increasing number of frequency modes that a handset needs to support imposes challenges on the design of the handset, especially its antenna and radio frequency (RF) components. Saving a half dB in power would mean a great deal in saving in battery life and improvement in the quality of handset phone reception. It is proven the antenna dynamic matching circuits can provide an improvement in reception of up to 3dB, compensating for the effects of the operating user [1]. In this paper, we propose an adaptive control system to compensate the power loss associated with the time-varying impedance mismatch in different operation modes of a wireless handheld device, used for communication, web browsing, media streaming, etc. Our goal is to minimize the impedance variations seen at the transceiver by tuning the matching network in real time, and hence to maximize the antenna performance for any device, user, and environment configurations.

Advantages of adaptive antenna matching have been widely proved using technologies such as voltage-controlled capacitors and capacitive switches. For instance, Chen et al. [2] designed a tunable matching network using an impedance transformer with thin-film Barium Strontium Titanate (BST) varactors to boost efficiency of a highly-reactive integrated antenna, and Bezooijen et al. [3] presented an adaptive control system based on impedance phase detection to compensate the imaginary part of antenna impedance using a tunable series-LC matching network with RF-MEMS capacitive switches. This paper follows [4-6], where the inventors proposed an adaptive matching technique based on multiple measurements of reflected power in uplink mode. We extend this approach and present three novel tuning methods based on iterative adjustments of tunable components. The computational and time complexities of adaptive match are investigated using an in-house prototype system with a tunable parallel-LC matching network.

II. PROPOSED IMPEDANCE MATCHING METHODS

A block diagram of an antenna system with tunable matching network is shown in Fig. 1. The mismatch level is determined by measuring the power of partially standing wave formed as a result of partial reflection of the incident wave. It is commonly described in terms of VSWR, or the voltage standing wave ratio, defined as the ratio of adjacent amplitude peaks of the standing wave. The VSWR is 1:1 for ideal transmission when the incident wave is fully transmitted. The objective of the tuning system is to minimize VSWR which increases as the antenna mismatch deteriorates.

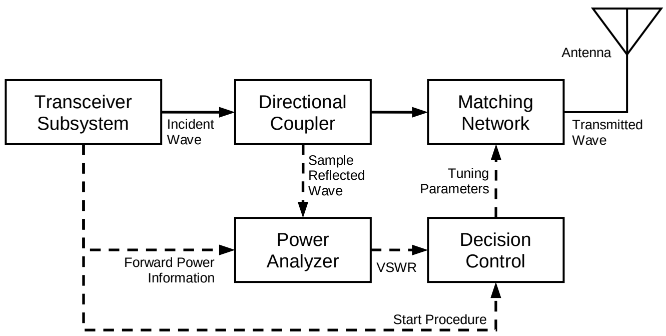

Fig. 1. Apparatus comprising the matching network, directional coupler, power analyzer and decision control module, with subsystem for gathering forward power information from the transceiver which may include power control data sent by the network, current drain, and so on.

The reflected power varies by tuning the matching network. The input impedance of antenna $Z_A = Z_R + jZ_I$ is obtained based on measurement of the power reflected from matching network P_R and the knowledge of the incident power P_I. Equation (1) describes the VSWR denoted by ν in terms of the absolute value of reflected coefficient at transceiver denoted by ρ:

$$\nu = (1+\rho)/(1-\rho), \tag{1}$$

where

$$\rho = \sqrt{P_R/P_I}. \tag{2}$$

Let $x = \langle X_1, X_2, \cdots \rangle$ denote the vector of tunable components of the matching network, i.e., the capacitance values,, states of switches, etc. At least two independent measurements are required to uniquely identify the real and imaginary parts of the antenna impedance. This is achieved by tuning the components x to different values $x^{(1)}$, $x^{(2)}$, … and measure the associated reflected power. Let $P_R^{(i)}$ denote the reflected power and $\rho^{(i)}$ denote the absolute reflected coefficient at transceiver when the matching network is tuned to $x^{(i)}$. We define $\eta^{(i)} = \langle x^{(i)}, P_R^{(i)} \rangle$ as the i-th measurement set, $i = 1, 2, \ldots$ and $S^{(i)} = \left[S_{11}^{(i)}, S_{12}^{(i)}, S_{21}^{(i)}, S_{22}^{(i)}\right]$ as the vector of scattering parameters (S-parameters, henceforth) of matching network tuned to $x^{(i)}$. For each set of measurements $\eta^{(i)}$, the absolute value of reflected coefficient at transceiver $\rho^{(i)}$ is described in terms of the reflected coefficient of antenna Γ_A in (3):

$$\rho^{(i)} = \left|S_{11}^{(i)} + S_{12}^{(i)} S_{21}^{(i)} \Gamma_A / \left(1 - S_{22}^{(i)} \Gamma_A\right)\right|. \quad (3)$$

where $\Gamma_A = \Gamma_R + j\Gamma_I$ is a complex number. Given reference impedance Z_o (typically 50Ω) and the reflected coefficient Γ_A, the antenna impedance Z_A is obtained from (4):

$$Z_A = Z_o\,(1 + \Gamma_A)/(1 - \Gamma_A). \quad (4)$$

We next introduce three methods proposed to dynamically match to Z_A.

A. Matching based on Calculation of Antenna Impedance

Given the impedance of antenna, the matching network can be straightforwardly tuned to maximize the transmitted power. As the range and resolution of variations of components x are known a priori, the matching process can be performed in two stages: *a) Calculation of Antenna Impedance:* To solve the system of equations (3) formed by measurement sets $\eta^{(i)}$, $i = 1, 2, \ldots$ for the real and imaginary parts of antenna impedance Z_A; and *b) Optimal Tuning:* To retrieve the pre-calculated optimal values of tunable components to match Z_A.

An advantage of the two-stage approach is that the antenna impedance is explicitly calculated, which facilitates disregarding inaccurate measurements. From (3), each pair of measurements $\eta^{(1)}$ and $\eta^{(2)}$ yields a system of two quadratic equations in terms of Z_R and Z_I, and hence up to two solutions for the antenna impedance. Not all solutions, however, are acceptable for a given antenna. Accordingly, inadmissible measurements are removed based on the known variation range of antenna impedance.

B. Matching based on VSWR Variations

The solution of antenna impedance is sensitive to changes in the power measurements, which are due to the low range of reflected power and bounded linear range of power detectors in practice. In a direct approach, the matching network can be iteratively tuned to minimize the antenna mismatch based on the gradient of VSWR computed as the difference associated with variations of tunable elements.

The VSWR minimization problem is bound constrained as each tunable element has a fixed variation range. Due to noisy measurements of the VSWR, the problem may have many local minima that are not of interest. Hence, an automated method must enforce convergence to the global minimum, e.g. by updating the difference increments as the iteration progresses.

TABLE I. PSEUDOCODE FOR ITERATIVE MATCH BASED ON VSWR VARIATIONS

[Initialization] Input values for tuneable components $x^{(1)}$ and step size h.	
[Recursion] For each iteration $i = 1, 2, \ldots$	
a.	Measure VSWR $\nu^{(i)}$ for current setting of tuneable elements $x^{(i)}$.
b.	Terminate if $\nu^{(i)} \leq \bar{\nu}$.
c.	Measure VSWR vector $\acute{\nu}^{(i)}$ for perturbed tuneable elements $x^{(i)} \pm h$.
d.	Compute vector of first-order partial derivatives $g^{(i)}$.
e.	Compute matrix of second-order partial derivatives $H^{(i)}$.
f.	Compute line search coefficient $l^{(i)}$ based on $\nu^{(i)}$ and $g^{(i)}$.
g.	Compute optimal purturbation level $d^{(i)}$ based on $g^{(i)}$ and $H^{(i)}$.
h.	Update $x^{(i+1)} = x^{(i)} - l^{(i)} d^{(i)}$.

TABLE II. PSEUDOCODE FOR ITERATIVE MATCH BASED ON COMMON USE CASES OF DEVICE

a.	Measure VSWR.
b.	Search constant VSWR circles for data structure containing closest VSWR value.
c.	Search constant VSWR circle element data, measuring VSWR for each element set.
d.	IF measured VSWR with specific element set is less than desired VSWR, then STOP
e.	ELSE search all quanta in selected VSWR circle and select element set having least VSWR value OR load element values previously determined for minimum VSWR for mobile device in free-space.

A pseudocode for iterative matching based on implicit filtering (e.g., see [7]) and quasi-Newton algorithm is described in Table I. The algorithm convergence rate depends on the initial set of tunable components $x^{(1)}$ and step size h. These values are predetermined based on the variation range of antenna impedance at common use cases of wireless device.

Steps (d) – (g) of the iterative match algorithm presented in Table I are implemented as sequences of elementary arithmetic operations based on the number and range of tunable components. The calculated steepest descent direction, however, may be invalid due to the error associated with approximation of gradient and Hessian values. This is fixed in step (f) by backtracking the line search (e.g., see [8, ch. 6]) where the difference increment is reduced if needed.

C. Matching based on Common Use Cases of Device

The third matching approach exploits the fact that each constant VSWR circle as viewed on the Smith chart (Fig. 3.) represents a set of complex impedances $Z_A = Z_R + jZ_I$ that may be further quantized into sets of values that match Z_A around the circle as closely as possible to $1 + j0$. Tuning is performed by searching the quantized values of tunable elements that produce a match from selected points on the circle associated with current VSWR. Searching a data structure representing these values is both rapid and bounded. The number and value of constant VSWR circles can be selected based on worst case situations in real world situations and may be optimized to produce reasonable results with minimum arithmetic. Tuning values around each circle may be as coarsely or finely quantized as needed. There are no tuning-range ending boundaries to be handled, as there would be a finite number of choices available.

The pseudo algorithm is presented in Table II. Adaptive matching based on either calculation of antenna impedance (II.A) or VSWR variations (II.B) is performed using sequences of arithmetic operations to iteratively tune the capacitors. There is not much computation associated with tuning based on common use-cases of device (II.C) and hence the algorithm runs faster than the other two. In addition to significant reduction of processing complexity, this method eliminates the boundary problems of a loop-based algorithm and addresses what to do if a solution is not found for some reason. Also eliminated is the non-linear artifacts associated with step sizes for reactive tuning elements, because in an actual loop-based matching network, having a fixed value of 1% is not only sub-optimal, but may not even be appropriate under certain conditions. There are cases in which a 5% step would be more appropriate and others, even for matching the same complex load impedance, where 0.5% would be required.

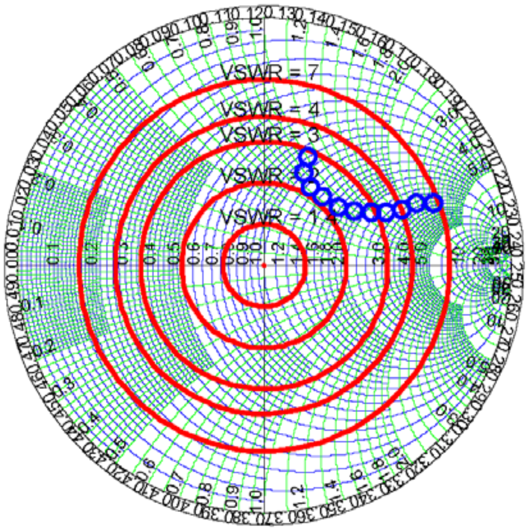

Fig. 2. Smith chart showing a) Constant VSWR circles (red) and b) Selected points (blue) representing variations of reflected coefficient of a plenary inverted-F antenna (PIFA) prototype held in hand at 1.8 GHz.

III. PROTOTYPE AND EXPERIMENTS

An in-house prototype board based on the block diagram of apparatus shown in Fig. 1 is built for the purpose of validating the three proposed methods, see Fig. 3. The board comprises a parallel-LC matching network with fixed inductance $L = 3.3\text{nH}$ and two tunable BST-based capacitors with range $2.40\text{pF} - 6.80\text{pF}$. A 16-bit microprocessor unit (PIC24FJ64-GB004) is used as the decision control module which takes reflected power as the input and outputs the control voltage signals to tune the BST capacitors. A power detector module is used to compute the power of reflected signal sampled by a unidirectional coupler.

The running time of each algorithm presented in Section II depends on the number of measurements required to find the optimal values of tunable components, and the computational cost associated with each tuning stage. The major complexity associated with the tuning method based on computation of antenna impedance (II.A) is the computation of S-parameters of matching network for each configuration of tunable components. This, however, can be done offline considering the fixed range and resolution of capacitors. Similarly, given the antenna impedance, optimal values of tunable components are obtained from a lookup table, populated knowing the range of variations of antenna resistance Z_R and reactance Z_I. Accordingly, using an external memory unit, the computational cost of each stage is limited to the series of arithmetic operations used to solve for the antenna impedance given the S-parameters. On average, each iteration of this algorithm runs in 19 milliseconds.

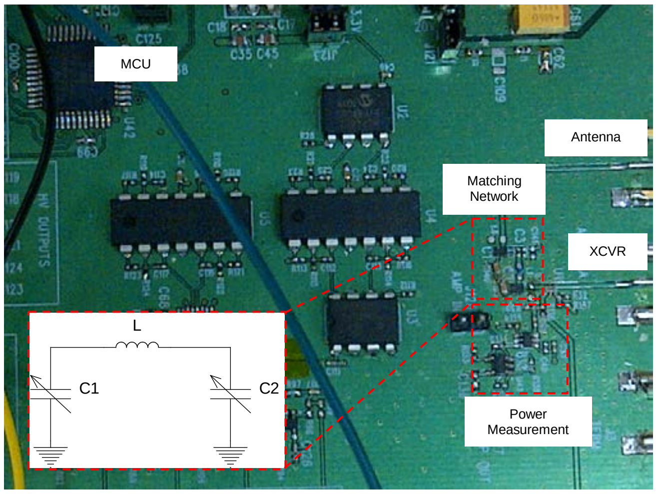

Fig. 3. System prototype comprising a matching network with two BST capacitors marked as C_1 and C_2 on the board, a microprocessor unit (MCU) as the decision control module, and a power measurement circuit.

The number of iterations needed to optimally tune the matching network depends on the initial configuration of capacitors and the magnitude and phase shift of the antenna impedance. In the case of two-stage tuning (II.A), multiple measurements are required to calculate the antenna impedance. This is partially due to fluctuations and inaccuracies of incident and reflected power levels. Figure 4 depicts the distribution of reflected power measurements and calculated VSWR for a plenary inverted-F antenna (PIFA) in 100 sample runs of the tuning algorithm, with fixed frequency and configuration of matching network. Considering the nonlinearities in power detection, at best an estimate of antenna impedance is obtained at each sample run of algorithm. Moreover, the power measurements provide no information about the phase of antenna impedance. Accordingly, additional measurements $\eta^{(i)},\ i = 1, 2, \ldots$ must be made to eliminate inadmissible solutions of the resulting system of quadratic equations (3).

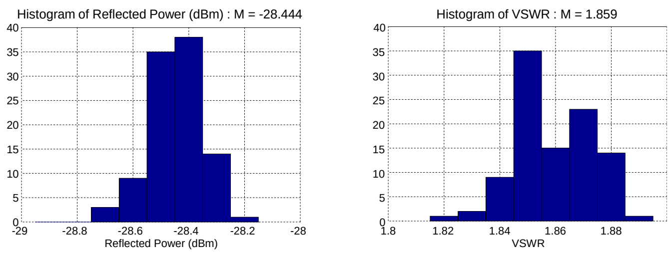

Fig. 4. Distribution of reflected power in 100 measurements for initial configuration of matching network $C_1 = 4.50$ pF, $C_2 = 3.90$ pF at 1.8 GHz.

Fig. 5 depicts results of 100 sample runs of the two-stage tuning algorithm (II.A) at fixed transmit frequency 1.8 GHz. At each run, the reflected power and VSWR are first measured (see Fig. 4) for the initial set up $\langle C_1 = 4.50\text{pF}, C_2 = 3.90\text{pF} \rangle$. Additional measurements shown in Fig (5a) are obtained for perturbed configuration $\langle C_1 = 4.20\text{pF}, C_2 = 3.50\text{pF} \rangle$. Accordingly, the optimal configuration of matching network (Fig. 5c) is obtained following calculation of antenna impedance (Fig. 5b).

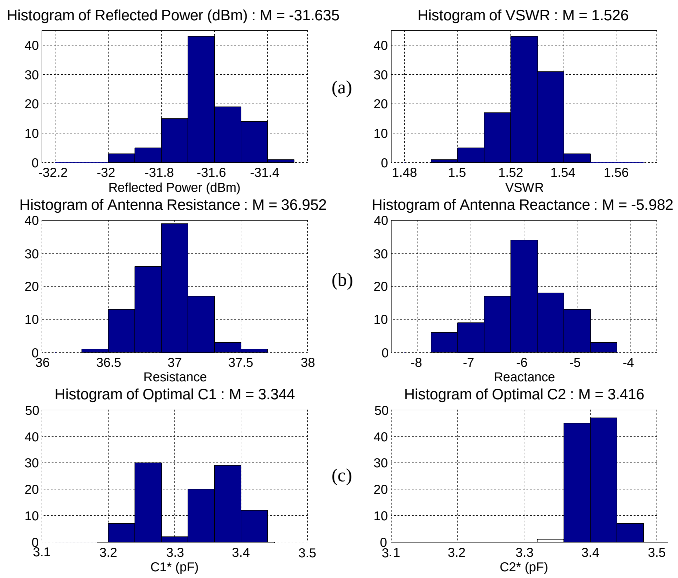

Fig. 5. Results of 100 sample run of matching method based on calculation of antenna impedance: (a) Distribution of power for perturbed configuration of matching network C_1 = 4.20pF, C_2 = 3.50pF (b) Distribution of antenna impedance (c) Distribution of optimal configuration of matching network.

More than two measurement sets are required to identify the antenna impedance if the system of equations (3) has no solution. This is demonstrated in Fig. 6, where on average 5.34 (median: 5) measurements are made to tune the matching network in 100 sample runs of the tuning algorithm with random initial settings and random perturbations in range [-10, 10] percent. The tuning performance is improved by adjusting the initial configurations of matching network to half (mean: 3.49, median: 3 measurements) and one-third (mean: 3.08, median: 3 measurements) of capacitance range.

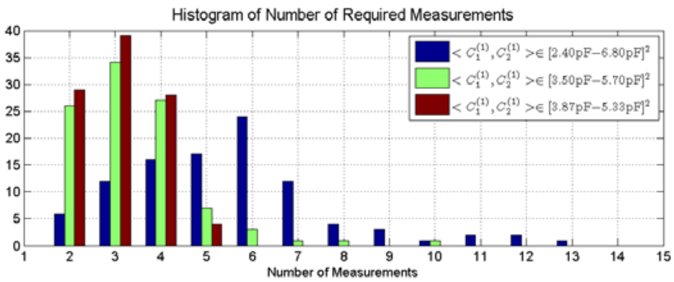

Fig. 6. Distribution of number of required measurements for unique identification of antenna impedance in 100 sample runs of the two-stage tuning algorithm (II.A) with random initial settings and perturbations.

In addition to the initial state, the running time of iterative tuning based on VSWR variations (II.B) depends on the impedance of antenna and maximum adjustments allowed (step size) at each stage. The tuning sequence is marked in Fig. 7 comparing two sample runs of the iterative tuning algorithm (II.B) with similar initial settings $\langle C_1 = C_2 = 3.90\text{pF}\rangle$ but different antenna impedance (a) $Z_A = 85 + j15$ and (b) $Z_A = 175 + j15$.

IV. CONCLUSION AND FURTHER DIRECTIONS

We propose three adaptive control methods to correct antenna mismatch based on power measurements in transmit mode. The first is based on the computation of the antenna impedance, the second is based on the VSWR, and the third is based on the device state. The proposed methods are validated with an in-house prototype, and are compared for accuracy, computational complexity and processing time.

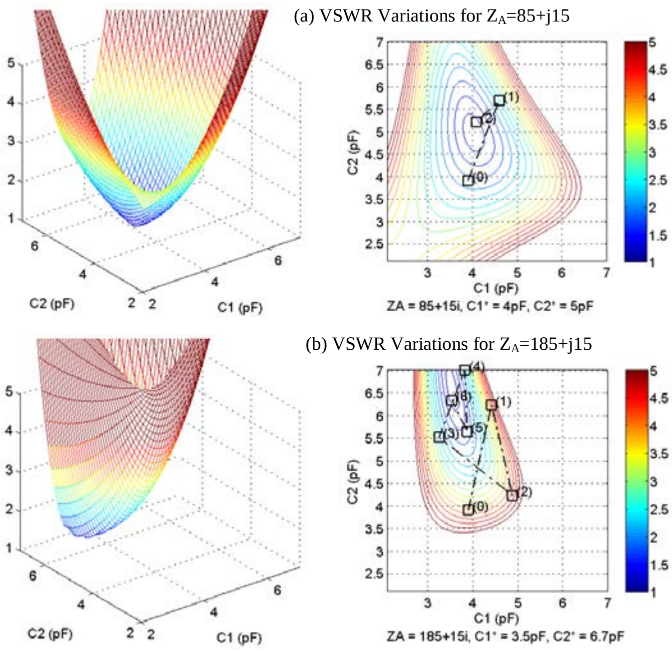

Fig. 7. Sample runs of iterative tuning based on VSWR variations. The optimal configuration is determined in (a) 2 and (b) 6 adjustments.

The antenna VSWR may increase abruptly by tuning based on calculation of antenna impedance and common use cases of device. This can be controlled by monitoring the VSWR variations and limiting the maximum adjustments, in expense of slowing down the tuning process. Accordingly, a combination of all three methods is advised in practice, with initial and reserve configurations set according to common use cases of device and fine tuning based on VSWR variations.

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