Speedy derivative-corrective mass spring algorithm for adaptive impedance matching networks

Y.C. Wong, T. Arslan, A.T. Erdogan, N. Haridas and A.O. El-Rayis

Adaptive impedance matching algorithms are used to preserve the link quality of mobile phones, under fluctuating user conditions. It is highly desirable to reduce the search time for minimising the risk of data loss during the impedance tuning process. Presented is a novel technique to reduce the search time by more than an order of magnitude by exploiting the relationships among the mass spring's coefficient values derived from the matching network parameters, thereby significantly reducing the convergence time of the algorithm.

Introduction: The demand for small size antennas is increasing for the next generation wireless devices. However, a small size antenna inherently has impedance that varies rapidly with frequency and the user's environment. This can cause substantial impedance variations over time, for instance the proximity of a mobile phone handset's antenna to the user's body. For this reason, an adaptive impedance matching network (AIMN) is required to correct antenna impedance mismatches and maximise the transmission power. Linear correlation methods, such as linear mean square (LMS), have been reported for tuning the real [1] and imaginary [2] parts of the antenna impedance. However, these methods are able to match either the real or imaginary part of the impedance but not both parts simultaneously owing to the nonlinear correlation of the tuner components. To correct both real and reactive mismatches, researchers applied a specific genetic algorithm (GA) [3, 4]. However, GAs are computationally very expensive and exhibit slow convergence speed. The tuning process of the adaptive impedance matching network changes the amplitude and phase of the signal radiated, hence transmitted data may be corrupted if tuning happens during transmission. Therefore, it is desirable to perform tuning during very limited idle periods in order to minimise the risk of data loss. This shows the need for a fast and computationally less complex algorithm to correct both real and reactive parts of antenna impedance mismatches. In this Letter, we propose a novel speedy derivative-corrective mass spring (DCMS) algorithm for adaptive impedance matching networks. The performance of the proposed algorithm is evaluated by simulations, demonstrating shorter convergence time compared to the GA and better accuracy compared to LMS based methods.

Derivative-corrective mass spring (DCMS) algorithm: An adaptive impedance matching network consists of tunable impedance that couples a load to a resistive generator over a frequency band of interest, as shown in Fig. 1*a*. Tunable impedance networks are mostly based on *LC*- or *Pi*-networks, as shown in Fig. 1*b*.

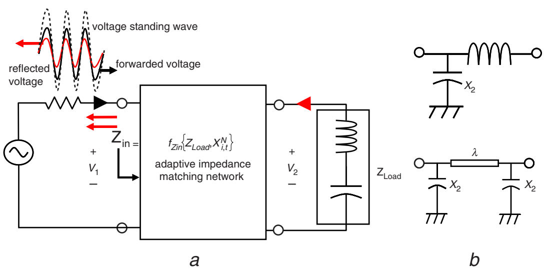

Fig. 1 *Block diagram of adaptive impedance matching network*

a Matching network parameters
b Common impedance networks: *LC*-network and *Pi*-network

The input impedance (Z_{in}) is a function of the load (Z_{Load}) and an array of tunable network parameters with N elements ($X^N_{i,t}$) [5]. The voltage standing wave ratio (VSWR) is used as a measure of impedance mismatch based on the reflection coefficient (Γ), as shown by (1) and (2).

$$\Gamma = \frac{f_{Z_{\text{in}}}\{Z_{Load}, X^N_{i,t}\} - 1}{f_{Z_{\text{in}}}\{Z_{Load}, X^N_{i,t}\} + 1} \tag{1}$$

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \geq 1 \tag{2}$$

The evolution of the proposed DCMS algorithm is governed by the fundamental second-order numerical differential method for a basic mass spring (BMS) [6]. The force exerted by the spring (F) is proportional to the stiffness of the spring (k) and the vicious damping coefficient (r), as shown by (3). Applying a finite-difference approximation for the BMS in (3), and incorporating the related network parameters in (1) and (2), we derive the next step velocity ($V^N_{i,t+1}$) and the displacement ($X^N_{i,t+1}$) of the spring, as shown by (4) and (5):

$$\begin{aligned} F &= m \times a = m \times \left(\frac{V^N_{i,t+1} - V^N_{i,t}}{dt} \right) \\ &= m \times d\left(\frac{X^N_{i,t+1} - X^N_{i,t}}{dt} \right) = -k \times X - r \times V \end{aligned} \tag{3}$$

$$\begin{aligned} V^N_{i,t+1} &= \frac{-k \times X^N_{i,t}}{m} + \left(1 - \frac{f\{VSWR\}}{m}\right) \times V^N_{i,t} \\ &= -k \times g_{ext} \times X^N_{i,t} + (1 - r \times g_{ext}) \times V^N_{i,t} \end{aligned} \tag{4}$$

$$\begin{aligned} X^N_{i,t+1} &= \left(1 - \frac{k}{m}\right) \times X^N_{i,t} + \left(1 - \frac{f\{VSWR\}}{m}\right) \times V^N_{i,t} \\ &= (1 - k \times g_{ext}) \times X^N_{i,t} + (1 - r \times g_{ext}) \times V^N_{i,t} \end{aligned} \tag{5}$$

In the BMS algorithm, a uniform r is used. However, in our proposed DCMS algorithm, parameter r is controlled by the VSWR while the VSWR is determined by Γ and Z_{in}, which are derived from the current displacement ($X^N_{i,t}$). Z_{in}, which is closer to the co-ordinate of the Smith chart, has lower VSWR; while Z_{in}, which is far from the centre of the Smith chart, exhibits higher VSWR. The parameter r is incorporated with $V^N_{i,t+1}$ and $X^N_{i,t+1}$, as shown in (4) and (5). A higher velocity is imposed on individuals which are located far from the centre of the Smith chart, as shown in Fig. 2*a*. Whereas, the velocity decays towards the centre of the Smith chart, making the individuals exploiting their current locations better. This enhances the convergence speed of the DCMS significantly compared to the BMS, as shown in Fig. 2*a*.

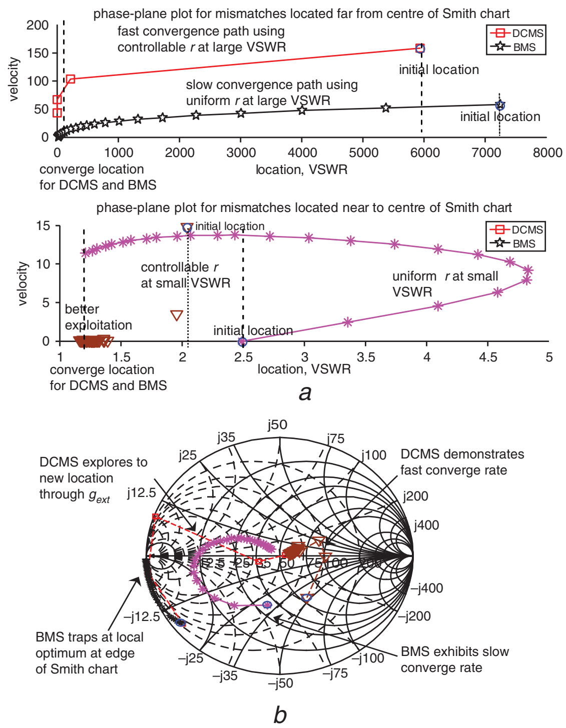

Fig. 2 *Comparison of proposed DCMS with BMS for different mismatches*

a Based on velocities and current locations of individuals in phase-plane plot
b Based on complex input impedances (Z_{in}) in Smith chart

The BMS will always be trapped in local optimum when the mismatch impedance is located at the edge of the Smith chart, as shown in Fig. 2*b*. For the proposed DCMS, an external random force ($0 < g_{ext} < 1$) is applied to re-tune the direction of convergence when the individuals go out of user-defined boundaries (e.g. $|imag(Z_{\text{in}})| > 100\ \Omega$) or the potential tuning parameters are invalid ($X_{i,t}^N < 0$). This external force in the DCMS circumvents the limitation of the numerical method which is sensitive to the initial values and enables better extrapolation to its neighbourhood.

Results and discussion: The DCMS algorithm was tested with two topologies, i.e. *LC*- and *Pi*-network. The algorithm stops as soon as a user-defined threshold for the VSWR is reached (e.g. VSWR < 2) or the maximum number of iterations (48) is exceeded. The results show that the DCMS outperforms both the LMS and the GA with its very fast convergence speed and high accuracy, see Figs. 3*a* and *b*. The LMS shows a moderate convergence speed compared to the DCMS owing to its constant step size. However, the LMS is unable to converge when both real and imaginary parts are involved in the tuning process, as shown in Table 1. The GA and the DCMS have close average convergence rates, although the GA's convergence rate could be improved further by allowing longer simulation time and increasing the number of chromosomes. However, the GA has the longest average CPU time which is more than 40 times slower compared to the DCMS.

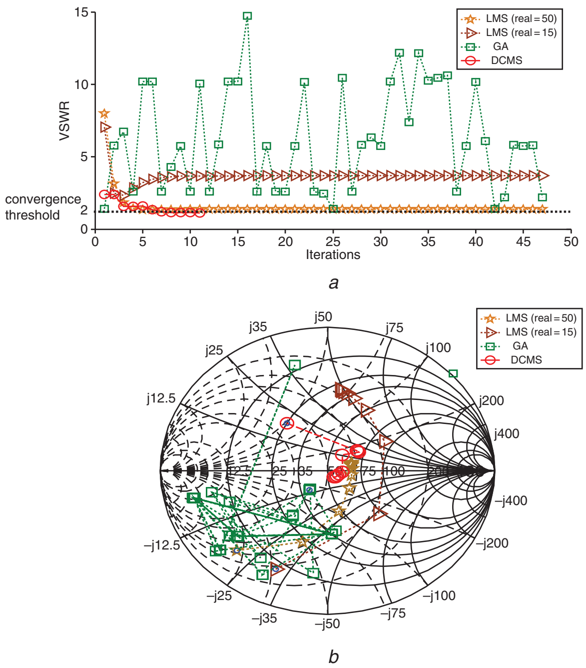

Fig. 3 *Convergence of LMS, GA and DCMS*

a Based on VSWR over number of iterations
b Based on complex input impedances (Z_{in}) in Smith chart

Table 1: Average VSWR and CPU time for DCMS, LMS and GA in 1000 runs based on *LC*- and *Pi*-network for mismatches involving both real and imaginary part of Z_{Load} (15 + j15.6) and solely the imaginary part of Z_{Load} (50 + j15.6)

Adaptive algorithm	AIMN	Elements in Z_{LOAD} to be corrected	Average VSWR	CPU time (ms)	Comments
DCMS	*LC*	Real and imaginary	1.7643	2.9	Fast and good convergence rate
		Imaginary only	1.2134	2.8	
	Pi	Real and imaginary	1.4561	12.4	
		Imaginary only	1.2053	13.1	
LMS	*LC*	Real and imaginary	6.3731	16.4	Unable to converge (VSWR > 2) for mismatches involving both real and imaginary parts
		Imaginary only	1.4539	18.9	
	Pi	Real and imaginary	3.6866	20.4	
		Imaginary only	1.0979	20.3	
GA	*LC*	Real and imaginary	1.3258	539.7	Slow CPU time
		Imaginary only	1.0879	536.9	
	Pi	Real and imaginary	1.3921	544.6	
		Imaginary only	1.2028	556.8	

Conclusion: For adaptive impedance matching networks, we have presented a novel derivative-corrective mass spring (DCMS) algorithm which has faster convergence speed and is more robust than existing algorithms, i.e. the LMS and the GA. The proposed DCMS algorithm can intelligently increase diversity and escape from local optimum traps, enabling it to converge to solutions faster. Moreover, it can adaptively determine the next step velocities and displacements, which significantly reduce the number of searching steps required. The reduction in search time is very important for reducing the risk of data loss and achieving better link quality for next generation green mobile applications.

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One or more of the Figures in this Letter are available in colour online.

Y.C. Wong, T. Arslan, A.T. Erdogan, N. Haridas and A.O. El-Rayis (*Advanced Smart Antenna Technologies Research Group, School of Engineering, The University of Edinburgh, Edinburgh, EH9 3JL, United Kingdom*)

E-mail: Y.Wong@ed.ac.uk

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