

An adaptive impedance matching approach based on fuzzy control

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Abstract. In this work an adaptive impedance matching scheme for 2.4GHz wireless communication, based on fuzzy control, is proposed. For that purpose, a two-port passive matching network controlled by a zero-order Takagi-Sugeno-Kang fuzzy controller is used, allowing the system to iterate until the matching point is reached. Several experiments using the fuzzy controller coupled to π , T , and L impedance matching networks are presented. Preliminary results derived from MATLAB 7.1 simulations of the described algorithm, and a comparison with a least mean square (LMS) impedance matching approach, are discussed.

I. Introduction

Wireless communications is currently a very important and fast-growing area of communications industry. Everyday faster and smaller communications systems for the transmissions of high-speed information, voice, video, and data are developed. As the operation speed of the communication systems increases, some integrity signal issues like reflection and crosstalk, which may produce important signal losses, become crucial [1,2]. Reflection is due to impedance mismatch between the source impedance and the load impedance. In this case, signal reflections traveling through the line are present in either, source to load or load to source, directions. Formulation of a complete mathematical model for impedance mismatch is a very complex process, since the parameters involved depend on many factors like process variations, length variations of the interconnection lines, temperature, etc. In this sense, knowledge based algorithms represent a very interesting alternative to be explored when looking for solutions to the impedance mismatch problem using adaptive schemes. Several approaches oriented to solve the problem of impedance mismatch have been reported in the last years: Yichuang et al. [3], presented an evolutionary tuning method for automatic impedance matching in radio communication systems based on genetic algorithms. Hemminger [4] reported an algorithm based on neural networks, aimed to perform real time impedance matching over a wide range of frequencies during transmitter operation, in the driving point impedance of an antenna. Munshi et al. [5] described a scheme for adaptive

impedance matching using a model reference adaptive controller, designed and implemented using adaptive delta-sigma filters, with a LMS approach. Genetic algorithms and neural networks have shown to have a good performance in adaptive matching systems; however they require a huge consumption of resources, which could make them impractical to be implemented on integrated circuits for applications in wireless portable devices. Sjoblom et al. [6] presented an adaptive impedance tuning unit based on switched shunt capacitor banks, however, the heuristics to detect the signal, compare signal strength, and operate switches through all states are not described. In this work, an adaptive impedance matching circuit based on a zero-order Takagi-Sugeno-Kang fuzzy controller, coupled to passive π , T , and L circuits, is presented. Fuzzy Logic, proposed by Zadeh [7], models the uncertainty of human thought and it offers a mathematical formalism, which attempts to emulate the scheme of human deduction. Fuzzy logic formalizes the treatment of vague knowledge, and approximates reasoning through inference rules, establishing the bases to generate practical solutions to problems where traditional methods, which may require precise mathematical models, could not be suitable. In this sense, fuzzy control represents a good alternative to be explored as a solution for the impedance mismatch problem through on-chip adaptive mechanisms.

II. Impedance Mismatch

Signal losses due to mismatch impedance are usually characterized through an estimation of the reflection coefficient, which is given by:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (1)$$

where Z_L and Z_0 are the load impedance and source impedance respectively. It is evident that the optimal matching point occurs when both impedances have the same value, or in the general case, when the load impedance is the complex conjugate of the source impedance. In wireless communication systems, many points of mismatch impedance which may produce reflections appear in the path of the signal. The first impedance mismatch occurs when the signal passes from the silicon wafer to the integrated circuit package. This is due mainly to the process variations which occur in the

integrated circuit process fabrication, causing that the interconnection pads exhibit impedance differences related to the initial design. A second impedance mismatch appears when the signal passes from the integrated circuit package to the printed circuit board (PCB), and it is related to the impedance values of the interconnections in the IC-PAD and the characteristic impedance of the transmission line in the PCB. The characteristic impedance of the transmission line depends on many factors such as: geometry, signal frequency, operation temperature, and distribution parameters, among others. Finally, there is another impedance mismatch when the signal passes from the PCB to the antenna. The input impedance of the antenna is strongly affected by nearby external objects and environmental conditions.

III. Fuzzy Controller.

In this paper, a zero-order Takagi-Sugeno-Kang fuzzy controller is used. Fig. 1 shows the basic structure of the proposed fuzzy controller. The system has one input corresponding to the error obtained from the difference between the output and the desired value, and one output which is further used to adapt the value of one capacitor in the well-known π , T , and L impedance matching circuits [8]. The error signal is fuzzified using three membership functions (S , Z , and Triangular Type), uniformly distributed over the input range with an overlapping degree of two. Fig. 2 shows form and distribution of the membership functions. The output is obtained using the defuzzification method referred as *center of gravity for singletons* (COGS) [9], which is given by equation 2 as follows:

$$u = \frac{\sum_i \mu(S_i) S_i}{\sum_i \mu(S_i)} \quad (2)$$

In this equation S_i represents the position of singleton i in the universe of discourse, and $\mu(S_i)$ represents the firing strength of rule i . The crisp output value u corresponds to the abscissa in the center of gravity of the fuzzy set, obtained from the aggregation of the values derived from the input singletons derived from the fuzzified error signal.

IV. Impedance Matching System.

Fig. 3 depicts a block diagram of the proposed general scheme for the impedance matching system. Here, the source impedance is modeled by Z_s , while the load is modeled by Z_L , both allowing complex values in the general case. In order to allow the impedance matching process, a two port network with a standard configuration π , T , and L , is inserted between the source and the load. The error signal is obtained by:

$$e(i) = C_i - C_t \quad (3)$$

Where C_i is the match network capacitor value at the i -th iteration, and C_t is the desired value of the capacitor, which is previously obtained by using basic circuit theory concepts. In an electrical implementation, the error signal can be obtained

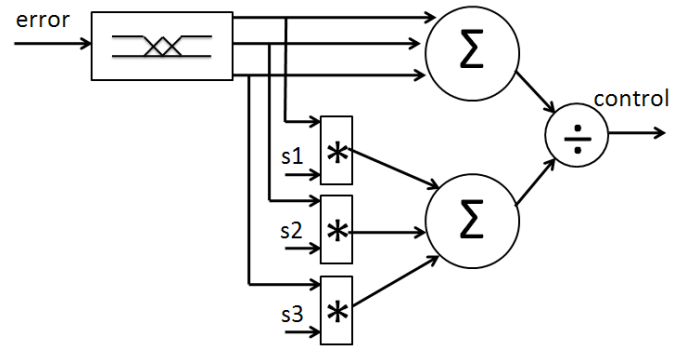


Fig. 1. General structure of the Fuzzy Controller.

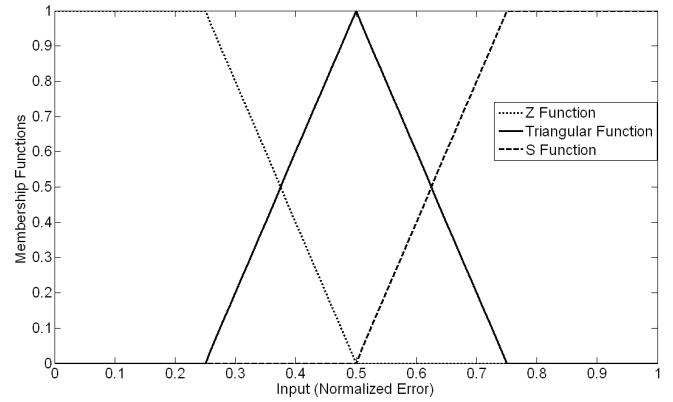


Fig. 2. Membership Functions of the input signal in the Fuzzy Controller.

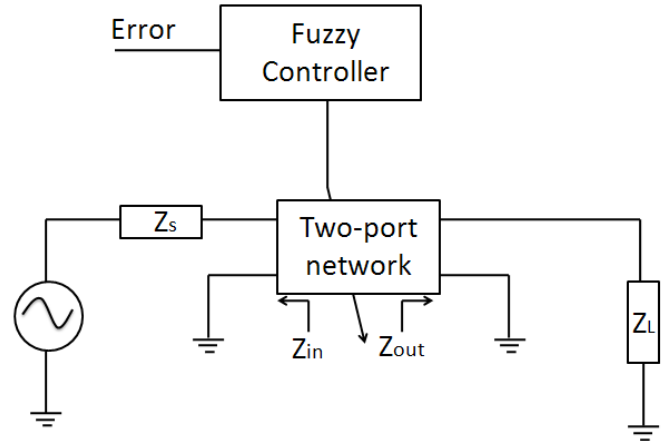


Fig. 3. Impedance matching system.

from the comparison between electrical signals, such as current or voltage. The error signal is used as the input to the Fuzzy Controller. After the fuzzy control process previously described, the system generates a control signal which modifies the impedance value of the two port impedance matching network. The system iterates until the input impedance value of the two port network Z_{in} becomes the complex conjugate of Z_s . In order to implement the two port impedance matching network, three configurations were used: π , T , and L type circuits. The system was simulated in

MATLAB 7.1 using s-parameter representation to model the two port network. The obtained results are shown in the following section.

V. Simulation results.

In order to perform the simulations, an initial set of values of the elements in the matching circuit was obtained using basic circuit theory concepts. The proposed initial values are:

- $R_s=50$
- $X_s=0$
- $R_L=25$
- $X_L=43.33$
- $C_{L-initial}=0.1\text{fF}$

The fuzzy controller iterates according to the process previously described, modifying in each step the value of the capacitor C_L , until the system reaches the matching point. Fig. 4 shows the evolution in time of the transfer function response given by equation 4, for the three network types.

$$H = 20\log\left(\frac{V_2}{V_1}\right) \quad (4)$$

As can be seen, the Fuzzy Controller adapts the impedance matching network, leading the system in every case to reach the point of $H=-3\text{ dB}$, which corresponds to the maximum power transfer. From fig. 4 it can be seen that the π network provides the faster convergence, reaching the matching point after 60 iterations in average. Fig. 5 depicts the system magnitude response in the frequency domain, after it has been adapted. Once the three networks achieve an adequate adaptation, the performance of the system is similar regardless the network type. As can be seen, the system has been designed to have a resonance frequency of 2.4GHz, which allow its implementation on wireless communication systems such as WI-FI [10] and Bluetooth [11].

For comparison purposes, a least mean square (LMS) algorithm was implemented, using the same impedance matching circuits. In a LMS adaptive system the criteria is to optimize temporal estimations of the error (5). This error is used to adapt the system through an iterative scheme, in a similar way to the fuzzy controller proposed in this work.

$$\rho(t) = -2\mu \int_{-\infty}^t e(u) \nabla_{\rho} e(u) du \quad (5)$$

Where $\rho(t)$ is an impedance matching coefficient, μ is constant, which establishes the adaptation speed of the system, $\nabla_{\rho} e(u)$ represents the gradient of the error related to the parameter ρ . The optimal value of the impedance matching coefficient ρ

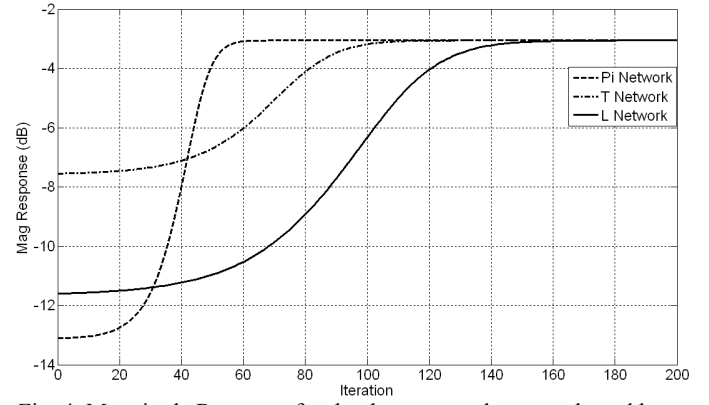


Fig. 4. Magnitude Response for the three network types adapted by the Fuzzy Controller.

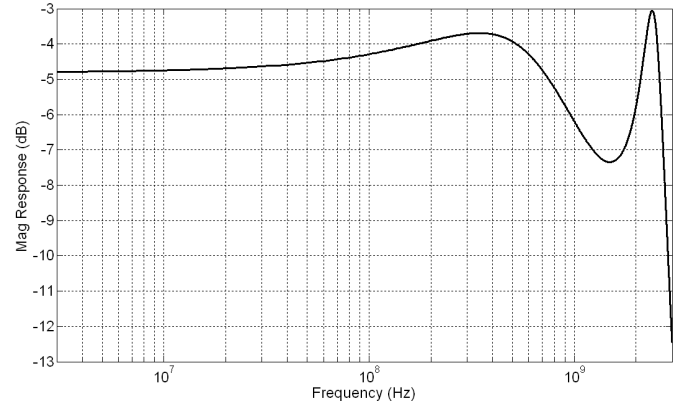


Fig. 5. Magnitud response in the frequency domain of adapted system.

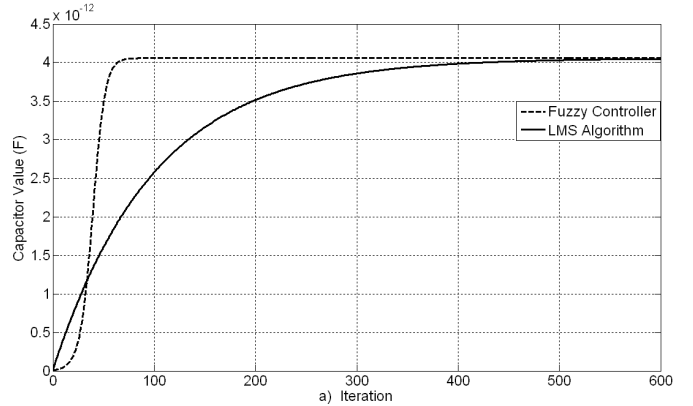


Fig. 6. Comparison between Fuzzy Controller and LMS Algorithm.

is achieved when the source impedance is equal to the load impedance.

Fig. 6 shows the results obtained in both cases: The fuzzy controller and the LMS algorithm. It can be seen that the Fuzzy Controller achieves the desired capacitor value in 80 iterations, compared to LMS algorithm which requires about 500 iterations, under similar conditions.

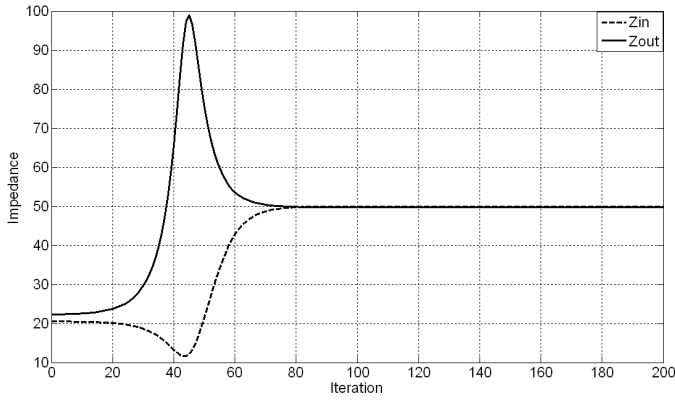


Fig. 7. Z_{in} and Z_{out} for π network adapted by the fuzzy controller.

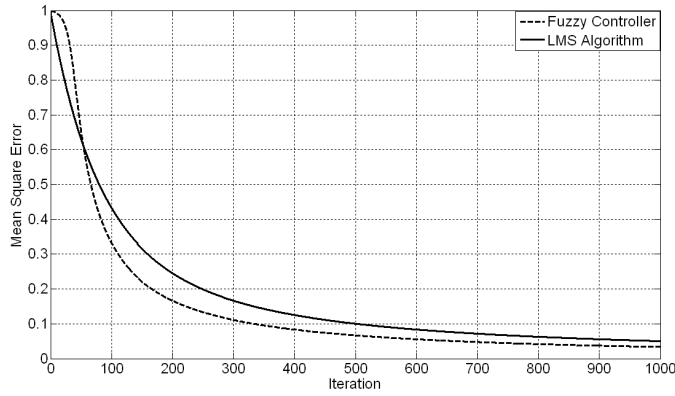


Fig. 8. Normalized Mean Square Error.

Fig. 7 shows a plot of the input and output magnitude impedances for the π network, obtained through the adaptive process with the fuzzy controller.

Fig. 8 shows a comparison of the normalized mean square error through the iterative process for the two cases: The proposed fuzzy controller, and the LMS algorithm. In both cases the π network was used as the impedance matching circuit. The normalized mean square error is given by eq. 6 as:

$$E[e^2(n)] = E[(d(n) - y(n))^2] \quad (6)$$

where $d(n)$ is the desired output and $y(n)$ is the actual output.

VI Conclusion.

This paper presented a novel scheme for adaptive impedance matching using a fuzzy controller, with application to wireless communication systems. Preliminary results based on MATLAB 7.1 simulations indicate that the proposed fuzzy controller represents a feasible and promissory scheme, aiming to the design and implementation of an on-chip adaptive impedance matching circuit. Experiments using three different matching network types, referred as π , T , and L , were carried out with excellent results. Among these experiments, the π network showed a faster convergence. The results

showed that the proposed fuzzy controller is in average six times faster than the LMS algorithm when the π network was used. The adapted system was designed to present a resonance frequency of 2.4 GHz, for applications in wireless communication systems such as WI-FI and Bluetooth. A VLSI design, simulation, manufacturing and characterization of the proposed adaptive impedance matching scheme, is currently in progress in our research group.

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