Optimum Power Transfer in RF-Front-End Systems Using Adaptive Impedance Matching Technique

Journal:	*Transactions on Microwave Theory and Techniques*
Manuscript ID	TMTT-2020-06-0578
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	04-Jun-2020

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Keywords:	LC impedance matching network (IMN), optimum power transfer, antenna impedance, RF-front-end transceiver, simple analogue circuits, couple of control-loops

1) What is the problem being addressed by the manuscript and why is it important to the IEEE TMTT community?

The demand for the higher data rate has necessitated the development new generation of mobile communication systems. Antennas interface the mobile communications devices to the transmission medium and their performance is affected by the environment such as the human body and/or other objects in its proximity. The environment can adversely affect the antenna impedance resulting in a mismatch with input of the RF front end [1-3]. This paper describes an effective adaptive antenna impedance matching control algorithm which has two cascaded control loops to independently control the impedance's real- and imaginary-parts. Voltage and current are monitored in the matching network to reliably control the impedance and thereby reduce insertion-loss (IL). In addition, the proposed technique operates autonomously.

2) What is the novelty of your work over the existing work?

The proposed technique uses a tuning algorithm that converges to a matching point and does not require complex mathematical modelling of the system including its nonlinear control components. The system employs digital circuitry to generate the timing signal and simple analogue components. It is shown reliable convergence is realised inside the LC network's tuning range. Furthermore, insertion-loss was minimised by using matching network components to monitor the voltage/current signals. The proposed technique enables autonomous control of adaptive antenna matching networks for optimum power transfer.

3) Provide up to three references, published or under review, (journal papers, conference papers, technical reports, etc.) done by the authors/coauthors that are closest to the present work. Upload them as supporting documents if they are under review or not available in the public domain. Enter "N.A." if it is not applicable.

[4] M. Alibakhshikenari, B. S. Virdee, C. H. See, R. A. Abd-Alhameed, F. Falcone, E. Limiti, "Automated Reconfigurable Antenna Impedance for Optimum Power Transfer," 2019 IEEE Asia-Pacific Microwave Conference (APMC), pp.1461-1463.

4) Provide up to three references (journal papers, conference papers, technical reports, etc.) done by other authors that are most important to the present work. Enter "N.A." if it is not applicable.

This is an extension of Ref. [2]. Additionally, we have provided a comparison section to comparing the proposed work with the recent and related literature focusing on the adaptive impedance matching techniques, which have been presented in Refs. [15-36].

The novelty of the propose work is: (i) automated tuning of LC impedance matching network to compensate for antenna mismatch with the RF-front-end; (ii) use of a tuning algorithm that converges to a matching point without the need of complex mathematical modeling of the system and nonlinear control components (varactor-diode) are taken into account to realise rapid convergence of impedance matching; (iii) varactor-diodes with any range of capacitance are applicable, (iv) employs digital circuitry for timing generation and simple analogue components; (v) reliable convergence is realized inside the tuning range of the LC network; (vi) reduces insertion-loss by using matching network elements to monitor voltage/current signals; and, (vii) enables autonomous control of adaptive antenna matching networks for optimum power transfer.

Optimum Power Transfer in RF-Front-End Systems Using Adaptive Impedance Matching Technique

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***Abstract*- Matching the antenna's impedance with the RF-front-end is an issue for optimum power transfer, which affects radiation efficiency. This paper describes a technique for automatically tuning an *LC* impedance matching network to compensate for antenna mismatch with the RF-front-end. The technique converges to a matching point and does not require complex mathematical modelling of the system comprising non-linear control components. The system implementing the technique employs digital circuitry for synchronization and to realize relatively simple analogue circuits. Reliable convergence is realised inside the adjusting range of the *LC* network using a couple of control-loops whose purpose is to independently control the *LC* impedance. The systems insertion-loss is reduced by using matching network components that monitor the voltage/current variations. The technique enables autonomous control of adaptive antenna matching networks for optimum power transfer.**

***Keywords*- *LC* impedance matching network (IMN), optimum power transfer, antenna impedance, RF-front-end transceiver, simple analogue circuits, couple of control-loops.**

I. Introduction

The demand for the higher data rate has necessitated the development new generation of mobile communication systems. Antennas interface the mobile communications devices to the transmission medium and their performance is affected by the environment such as the human body and/or other objects in its proximity. The environment can adversely affect the antenna's impedance resulting in unwanted mismatch at the input of the RF-front-end [1]-[3]. In the transmission-mode and under the worst-case scenario the mismatch in the impedance can adversely affect the power-amplifier performance resulting from reflected power, which is likely to reduce the life of the battery due to excessive energy consumption [4]. In the receive mode, the carrier-to-noise ratio is degraded.

To resolve the issue with impedance mismatch, isolators can be used however they can undermine the maximum radiated power and efficiency. In addition, isolators have a narrow bandwidth and therefore are unsuitable for multiband phones. Alternatively, the quality of the link can be maintained by applying adaptive impedance matching techniques [5],[6]. This technique is popular for maintaining system performance parameters, i.e. optimum radiated power, linearity of power-amplifier, sensitivity of receiver, and power-efficiency. Moreover, its applicable for wireless systems operating at multiple bands as it enables a single impedance matching network (IMN) to suffice. However, the use of adaptive IMN in wireless systems are incumbered by stringent criteria on insertion-loss (*IL*), degree of linearity, and tuning span. The use of adaptively controlled IMNs [7],[8] is only possible with the availability of highly linear and high Quality-factor tuneable components such as RF microelectromechanical (MEM) devices [9],[10], CMOS-switches [11],[12], silicon and Barium-Strontium-Titanate (BST) varactor diodes [13],[14].

Recent works reported in literature on adaptive impedance-matching include: (i) a T-shaped adaptive impedance matching system that refers to predetermined load-Q information for different matching conditions to implement the impedance matching [15]. Here the T-shaped network uses tuneable capacitors that are controlled by digital relays. The frequency range for tuning is limited to between 10-95 MHz; (ii) the use of fuzzy inference system to construct the mapping relationship between load impedance and the matched capacitor set [16]. This technique is applied to optimise power transfer between coupled coils at a fixed frequency; (iii) the use of a machine learning strategy based on neural networks for the real-time range-adaptive automatic impedance matching of wireless power transfer applications [17]. Here the voltage controlled variable capacitors are employed in a π-type matching circuit. The matching is implemented for different gap spacing between the transmitter and receiver coils at a fixed frequency; and (iv) using RF MEMS based on a coplanar waveguide based on suspended bridges for impedance tuning [18]. The tuning is controlled by a variable applied DC voltage to the bridges over 1-6 GHz.

This paper describes an effective adaptive antenna impedance matching control algorithm. The IMN includes a couple of control-loops for independently controlling the impedance. It senses the voltage/current in the matching network to reliably control the real and imaginary parts of impedance and thereby reduce *IL*. In addition, the proposed technique operates autonomously.

Rest of the paper has been organized as follow as. The proposed approach to control antenna-impedance matching has been described in Section II. Section III presents controlling antenna-impedance matching based on LC network, which has been divided to two sub-sections of (i) series LC network, and (ii) parallel LC network. Adaptive control of parallel LC network has been illustrated in Section IV. Next section explains the LC-network adjusting zone. The Insertion loss has been presented in Section VI. Finally the paper has been concluded in the last Section VII.

II. Proposed Approach to Control Antenna-Impedance Matching

The proposed configuration of the adaptive matching system is depicted in Fig.1. In the transmit mode it consists of a matching network, directional coupler for mismatch measurement, a switch, switching timing generator, and time constant generator. Varactor diodes in the matching network provide electronically controllable capacitance. The system uses the magnitude of the return-loss (Γ) that is measured between the RF-source and the matching circuit input for impedance matching. As information on the Γ phase is also essential to minimize the degree of mismatch the system uses a test signal to determine whether the mismatch increases or decreases. This information is used to precisely control the capacitance in the matching network.

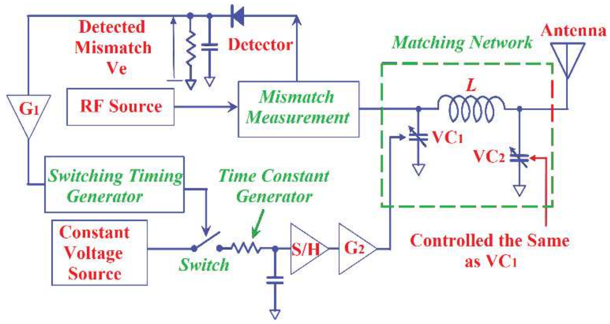


Fig.1.Configuration of the proposed adaptive matching system.

Protocol used here for adaptively matching involves measuring the degree of mismatch with the detection circuitry. This is achieved by turning the switch 'on' to increase the control voltage to the varactor#1 (VC_1). If the mismatch worsens the system acknowledges this and turns the switch 'off'. If the mismatch reduces the system acknowledges this by keeping the switch 'on'. This is maintained for the period of the control frame for VC_1. In the time frame period of VC_1, the control voltage to the varactor#2 (VC_2) is maintained at the value of the last time frame of the VC_2. The voltage is maintained using the sample-and-hold circuitry. At the end of the time frame period of VC_1, the control voltage for VC_1 is maintained and the time frame period commences for VC_2. Compared to other conventional techniques that use the steepest descent algorithm for optimization, the merits of the proposed system are: (i) no need for complex mathematical modelling; (ii) the nonlinearity of the control elements (varactor-diode) are taken into account to realise rapid convergence of impedance matching; and (iii) varactor-diodes with any range of capacitance are applicable. As it is not possible to obtain a desired varactor-diode with the required capacitance range the only option therefore is to use an available varactor-diode with a broader capacitance range. In the system an appropriate inductance L needs to be chosen, which is determined by simulation through parametric analysis. To characterise the improvement in impedance mismatch time characteristics of the return-loss between the matching network and the RF-front-end was used.

III. Controlling Antenna-Impedance Matching Based on *LC* Network

In the proposed technique the *LC*-network is extended in comparison to Ref. [2] to include two loops comprising a serial *LC* sub-loop and a parallel *LC* sub-loop that are independent from each other, as shown in Fig.2. These loops can now control components constituting the impedance matching network. The control loops essentially convert an undefined load admittance Y_{load} to the required matching impedance Z_{match} represented by [2]

$$Z_{match} = R_{match} + j\,X_{match} \qquad (1)$$

The loop#1 controls the parallel and series capacitors $C_{parallel_1}$ and C_{series_2}, respectively, constituting the imaginary-part of the match impedance X_{match}. The loop#2 controls the parallel and series capacitors $C_{parallel_3}$ and C_{series_4}, respectively, to set R_{match}. R_{match} is the real-part of the match impedance. The intermediate impedance ($Z_{intermediate}$) is given by [2]

$$Z_{intermediate} = R_{intermediate} + j\,X_{intermediate} \qquad (2)$$

If loop#2 is frozen and the amplifier-gain .errors A_{error_3} and A_{error_4} become significant, the signal errors S_{error_3} and S_{error_4} will be insignificant.

$$R_{intermediate} = 1 + \frac{R_{ref2}}{K_{dr2}} \qquad (3)$$

Where R_{ref2} and K_{dr2} are the magnitude of the reference and the detector constant, respectively, of loop#2 setting R_{match}. Loop#2 introduces an intermediate reactance defined by

$$X_{intermediate} = \frac{K_{dx2}}{X_{ref2}} - 1 \qquad (4)$$

Where X_{ref2} and K_{dx2} are the magnitude of the reference and the detector constant, respectively, of loop#2 setting X_{match}. Similarly, if loop#1 is frozen and the amplifier-gain errors A_{error_1} and A_{error_2} are significant, the signal errors S_{error_1} and S_{error_2} will be insignificant .and, .by .approximation, .hold .true

$$R_{match} = 2 + \frac{R_{ref1}}{K_{dr1}} + \frac{R_{ref2}}{K_{dr2}} \qquad (5)$$

Where R_{ref1} and K_{dr1} are the magnitude of the reference and the detector constant, respectively, of loop#1 setting R_{match}. Loop#1 introduces .an intermediate reactance X_{match} defined by

$$X_{match} = \frac{K_{dx1}}{X_{ref1}} + \frac{K_{dx2}}{X_{ref2}} \qquad (6)$$

Where X_{ref1} and K_{dx1} are the reference value and the detector constant, respectively, of the first loop setting X_{match}. From Eqn. (1) Z_{match} can be written as

$$Z_{match} = 2 + \frac{R_{ref1}}{K_{dr1}} + \frac{R_{ref2}}{K_{dr2}} + j\left(\frac{K_{dx1}}{X_{ref1}} + \frac{K_{dx2}}{X_{ref2}}\right) \qquad (7)$$

Eqn. (7) confirms the matched impedance is not dependent.of Y_{load}, the amplifier gain errors, and. the magnitude of the matching-network .components.

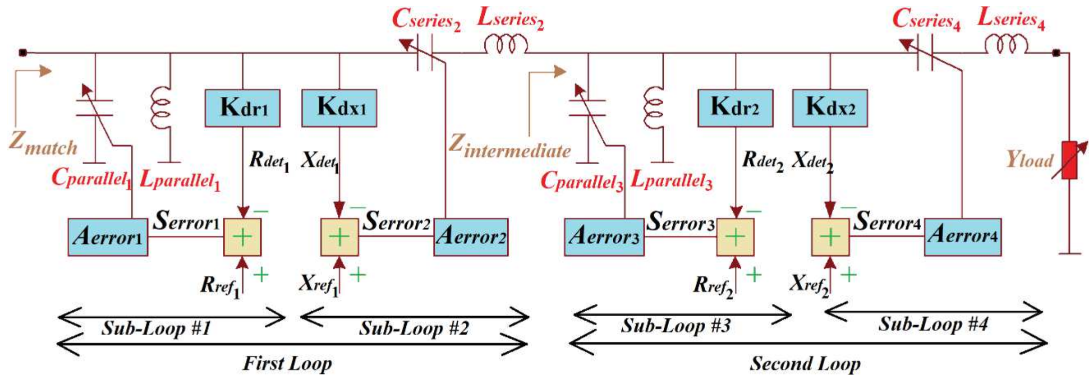
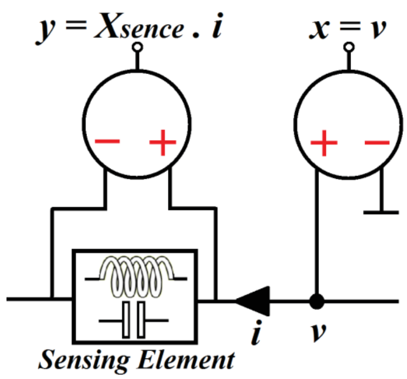


Fig.2. Schematic diagram for independent control of the matched impedance Z_{match} of an *LC* network.

Monitoring impedance. mismatch involves monitoring of RF signal and converting it to. *dc*. As the impedance is a function of voltage and current, the RF voltage. and RF current. can be sensed to establish the impedance. Fig.3 shows the point of voltage measurement *"v"* and differential. voltage. across a. monitoring component is used to measure the current. *"i"* and hence its reactance. X_{sense} can be determined. The monitoring component can be either an inductance or. capacitance that .is part of the tuneable IMN. The impedance at the node Z is determined by taking the ratio between the outputs of the two buffer-amplifiers in Fig.3.



$$Z = \frac{x}{y} X_{sense} \quad (8)$$

$$Y = \frac{y}{x} \frac{1}{X_{sense}} \quad (9)$$

Fig.3. Impedance Z or admittance Y can be deduced by sensing the voltage "*v*" and current "*i*".

Individual components representing the impedance can be determined from the *RF* signals. '*x*' and *'y'* using the detector. configuration shown in Fig.4. Impedance detection requires applying voltage information to input *'x'*

$$x = A_x \cos\left(\omega . t + \theta_x\right) \quad (10)$$

and current information.to input *"y"*

$$y = A_y \cos\left(\omega . t + \theta_y\right) . \left|\frac{1}{X_{sense}}\right| . e^{j\frac{\pi}{4}} \quad (11)$$

Input signal *'x'* is fed the first three mixers, i.e. to *mixer* #1 with 90° shifted in phase, to *mixer* #2 with a limited amplitude, and to *mixer* #3. Whereas input signal *'y'* is fed to the same mixers with 90° shifted in phase and is also applied to *mixer* #4 with limited amplitude to generate cosine and sine terms of the phase difference between *'x'* and *'y'*, both corresponding to magnitudes A_x and A_y. *Mixers* 1 & 2, and *mixers* 3 & 4 are used to find the magnitudes A_x and A_y of input signals *'x'* and *'y'*, respectively. The output signal of *mixers* #1 & #2 is split by the output signal of *mixers* #3 & #4 and vice versa to obtain the detected impedance Z_{detect}, represented by

$$Z_{detect} = R_{detect} + jX_{detect} \quad (12)$$

where
$$R_{detect} = \frac{a \times b}{d} \quad (13)$$
$$X_{detect} = \frac{c \times d}{a} \quad (14)$$
$$\theta_{detect} = \theta_x - \theta_y \quad (15)$$

where *a*, *b*, *c*, and *d* are defined as

$$a = 2\pi A_x \cos(\theta_{detect}) . \frac{1}{X_{sense}} \quad (16)$$
$$b = \frac{\pi}{2} A_x \sin(\theta_{detect}) \quad (17)$$
$$c = \pi A_y \cos(\theta_{detect}) \quad (18)$$
$$d = \frac{\pi}{2} A_y \sin(\theta_{detect}) . \frac{1}{X_{sense}} \quad (19)$$

From Eqn.(16)-(19), the real and imaginary parts of the detected impedance are specified as follow as:

$$R_{detect} = \frac{2\pi A_x^2 \cos(\theta_{detect}) \sin(\theta_{detect})}{A_y \sin(\theta_{detect})} \quad (20)$$

$$X_{detect} = \frac{\pi A_y^2 \cos(\theta_{detect}) \sin(\theta_{detect})}{4 A_x \cos(\theta_{detect})} \quad (21)$$

By combining Eqns. (20) and (21) the impedance detected is given by

$$Z_{detect} = \frac{2\pi A_x^2 \cos(\theta_{detect}) \sin(\theta_{detect})}{A_y \sin(\theta_{detect})} + j \frac{\pi A_y^2 \cos(\theta_{detect}) \sin(\theta_{detect})}{4 A_x \cos(\theta_{detect})} \quad (22)$$

According to Eqns. (20) and (21), the detected values of the impedance are independent of the frequency. This means frequency compensation is not required for high accuracy across a wideband frequency. The detected values of the impedance are related .to the ratios $\frac{A_x}{A_y}$ and $\frac{A_y}{A_x}$, hence they are.

independent. of the power of the *RF* signal transmitted. Moreover, according.to Eqn. (15), θ_{detect} is the differential phase difference between θ_x and θ_y.

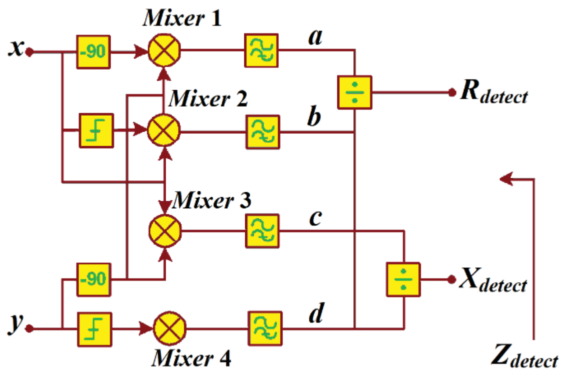


Fig.4. Quadrature detector that generates the constituent parts of the detected impedance from the return-loss.

By simply exchanging the detector input signals *'x'* and *'y'* the detector. generates the real-. and imaginary-parts of the admittance. When input signals *'x'* and *'y'* represent. the reflected and incident power, the detector generates a reading. of return-loss (*Γ*). The accuracy of the detector over a wide output power range, which is essentially dependent on limiter. and its amplitude. dependent. phase-delay, is traded-off. against power. consumption. The detector needs to be operated at a lower 'on/off' duty-cycle (<1%) to conserve power since the settling time of the detector is normally short (10-100 □*s*) compared. to the impedance variation of the antenna. The detector is susceptible to receiving unwanted signals as it's not frequency selective. These signals can cause the direction of the energy flow to change when they are stronger than the transmit signal. In that case the detector. reads the network. impedance. seen into the reverse. direction. However, at lower output. power (<0.dBm), there is no advantage from .adaptive .impedance .matching, and the .detector .can .be .turned . 'off' to prevent erroneous control.

A. Series LC Network

In Fig.5, the matched impedance Z_{match} of a series *LC* network represents the tuneable network of the sub-loops 3 and 4 of the first and second loops, respectively, in Fig.2, and is given by

$$Z_{match} = R_{match} + jX_{match} \tag{23}$$

in which the matched reactance X_{match} is given by

$$X_{match} = X_{L_{series}} + X_{C_{series}} + X_{load} \tag{24}$$

where

$$X_{L_{series}} = X_{L_{series\,2}} + X_{L_{series\,4}} \tag{25}$$

and

$$X_{C_{series}} = X_{C_{series\,2}} + X_{C_{series\,4}} \tag{26}$$

and the matched resistance R_{match} is

$$R_{match} = R_{load} \tag{27}$$

Tuning the series capacitor values C_{series} affects X_{match}, which is a function of tuning reactance ($X_{C_{series}}$), whereas. the matched. series. resistance (R_{match}) .is equivalent to load resistance. (R_{load}). In adaptive. matching. .networks, the orthogonal property of .resistance and .reactance is exploited in the .adaptive *LC* network to modify the matched .reactance (X_{match}) to the required .value .without .affecting the .matched .resistance (R_{match}).

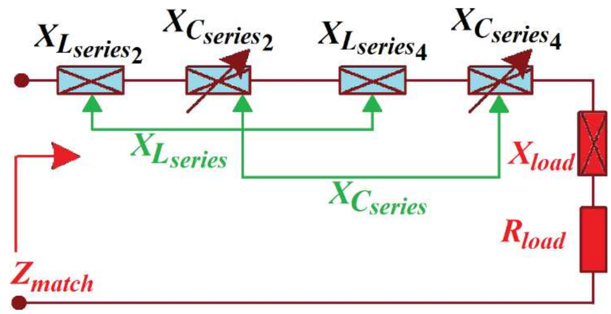


Fig.5. Adjustable *LC* network to provide the required inductive and capacitive load reactance.

The proposed series *LC* network is used to alter the real-part of the matched admittance. The matched impedance (Z_{match}) can be represented by matched admittance given by

$$Y_{match} = G_{match} + jB_{match} \tag{28}$$

where
$$G_{match} = \frac{(R_{load})^2 + (X_{match})^2}{R_{load}} \tag{29}$$

and
$$B_{match} = \frac{(R_{load})^2 + (X_{match})^2}{X_{match}} \tag{30}$$

The matched conductance (G_{match}) is a .symmetric .function of X_{match} .with a maxima of $1/R_{load}$. Consequently, a .series *LC* network, shown in Fig.6, can only convert load resistance R_{load} to a conductance that is smaller than $1/R_{load}$. Two solutions. exist for. the condition $G_{match} < 1/R_{load}$ .given. by

$$X_{match} = \frac{R_{load}}{G_{match}}\sqrt{(1 + G_{match}R_{load})} \tag{31}$$

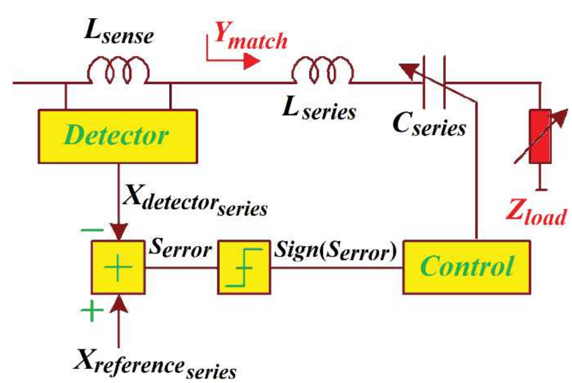


Fig.6. Series.*LC* network to control the real-part of the matched.admittance G_{match}.

Substitution of Eqn. (31) into (30) gives corresponding matched susceptance given by

$$B_{match} = \sqrt{\left(\frac{R_{load}}{G_{match}} + G_{match}R_{load}\right) + 1} \qquad (32)$$

B. Parallel LC Network

Fig.7 shows the matched admittance Y_{match} of a parallel LC network and representing the tuneable network of the sub-loops 1 and 3 of the first and second loops, respectively, (see Fig.2), is defined as

$$Y_{match} = G_{match} + jB_{match} \qquad (33)$$

Where

$$B_{match} = B_{L_{parallel}} + B_{C_{parallel}} + B_{load} \qquad (34)$$

$$B_{L_{parallel}} = B_{L_{parallel\,1}} + B_{L_{parallel\,3}} \qquad (35)$$

$$B_{C_{parallel}} = B_{C_{parallel\,1}} + B_{C_{parallel\,3}} \qquad (36)$$

and the matched conductance G_{match} is presented by

$$G_{match} = G_{load} \qquad (37)$$

Matching admittance (Y_{match}) of this parallel.LC-network corresponds. to. $Y_{intermediate}$ of the LC-network. The matched susceptance (B_{match}) is a function of tunable susceptance ($B_{C_{parallel}}$), .whereas the matched. conductance. G_{match} is equal .to load conductance G_{load} and independent $B_{C_{parallel}}$. $Y_{match}(C_{parallel})$ and the orthogonal. property of conductance/susceptance can .be exploited for adaptive. control. of the IMN by tuning the matched susceptance to the required .value without adversely affecting the matched conductance.

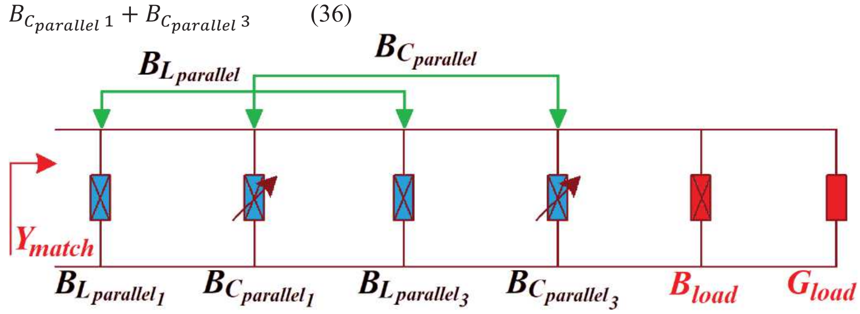


Fig.7. Variable parallel LC network and its matched admittance Y_{match}.

Moreover, the parallel LC network. allows control of the real-part of R_{match}. Matched admittance. (Y_{match}) can be represented by matched. impedance (Z_{match}) thus

$$Z_{match} = R_{match} + jX_{match} \qquad (38)$$

where

$$R_{match} = \frac{G_{load}+B_{match}}{(G_{load})^2} \qquad (39)$$

$$X_{match} = \frac{G_{load}+B_{match}}{(B_{match})^2} \qquad (40)$$

In Fig. 8, R_{match} is a.symmetric function. of B_{match} with a maxima of $1/R_{load}$. .

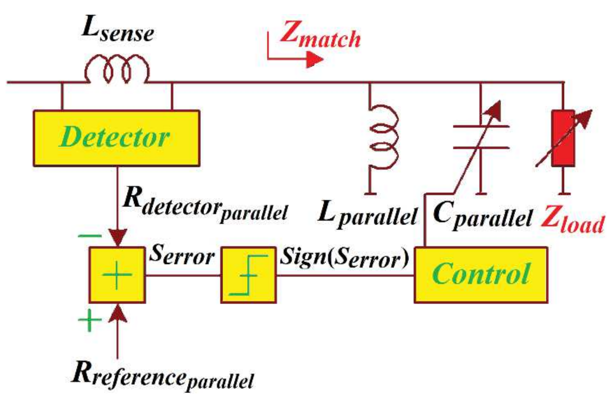


Fig.8. Parallel LC network to control the real-part of the matched impedance R_{match}.

Hence, a parallel. LC. network. can transform load conductance (G_{load}) to a .resistance that.is smaller than $1/R_{load}$. When $R_{match} < 1/G_{load}$, two solutions are obtained from Eqn. (39) and given by

$$B_{match} = \frac{R_{match}}{G_{load}}\sqrt{(1 + R_{match}G_{load})} \qquad (41)$$

Substitution of Eqns. (36) into (35) gives the two matched reactances

$$X_{match} = \frac{G_{load}}{R_{match}}\sqrt{(R_{match}G_{load}) + 1} \qquad (42)$$

IV. Adaptive Control of Parallel LC Network

The algorithm that was developed determined the convergence operation of the control loop. In fact, the tuneable capacitor, which is essentially a switched-capacitor array, is controlled by the sign of the error signal *SIGN*(S_{error}) generated from the series and parallel control loops. The up/down counter (U/D) is used to store the value of the control array. The output of the U/D is incremented or decremented in steps of one least significant bit, which depends on the error signal.

The convergence operation can be examined in open-loops conditions. At the controller when the loops (Figs. 6 and 8) are opened we sense *SIGN*(S_{error}) across the entire. ranges of X_{match} and B_{match}, SIGN(S_{error}) is +1. Hence, the directions of capacitor controls shown in Fig. 6 and 8 are not definitive. This can be resolved by using the detected. information on. the signs .of .the .matched susceptance *SIGN*(-B_{match}) and the matched reactance *SIGN*(-X_{match}), respectively, as a secondary .control criterion. shown in Fig.9 by dotted green blocks. The secondary feedback path allows the series and parallel control. loops. Criteria to be determined by the two detection. thresholds. for each loops of $G_{match} = R_{reference_{series}}$ and $B_{match} = 0$ (for series control. loop shown in Fig.6) and $R_{match} = R_{reference_{parallel}}$ and $X_{match} = 0$ (for parallel control loop. shown in Fig.8). Assuming. that detector. constants K_{series} and $K_{parallel}$ are equated to one,. S_{error} is now represented by

$$S_{error_{series}} = SIGN(-B_{match}) \cdot R_{reference_{series}} - R_{detector_{series}} \tag{43}$$

$$S_{error_{parallel}} = SIGN(-X_{match}) \cdot R_{reference_{parallel}} - R_{detector_{parallel}} \tag{44}$$

As $R_{reference}$, R_{match} and G_{match} are always positive, error signal S_{error} becomes strongly negative when $SIGN(-X_{match})$ and $SIGN(-B_{match})$ are negative. Hence, $SIGN(S_{error})$ is now unambiguous, and the first and second loops converge .reliably .to .operating .over the .entire .range of B_{match} and X_{match}.

The impedance matching network characteristics are applied to create .an adaptive *LC* network. that comprises a pair of loops, as shown in Fig.9. Control loop#1 sets the real-part of R_{match}. The sensing inductor L_{sense} consists of the series *LC* network controlled by the both loops. The loop#2 transforms the matched reactance X_{match} to $X_{reference}$. In fact, no information. on the real-part of the matched impedance is required. This makes. $R_{detector}$ surplus to requirement. If X_{match} is controlled iteratively the sign of $X_{detector}$ is significant.

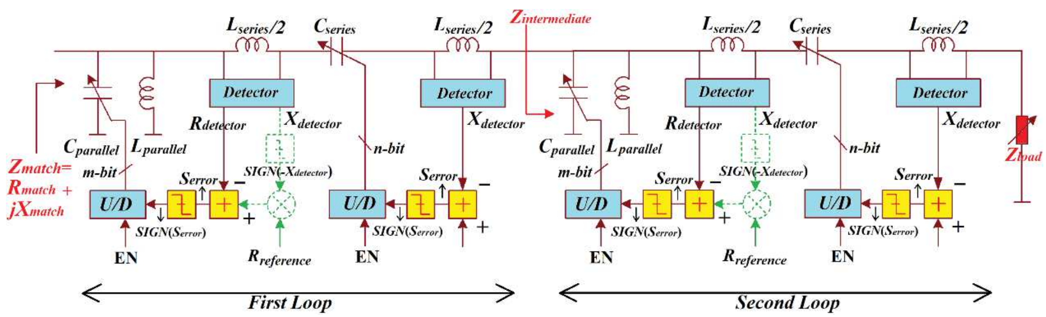


Fig.9. *LC* network implemented. An extra feedback path is shown in dotted 'green' blocks. This feedback ensures the first and second loops to function in their stable regions.

V. *LC*-Network Adjusting Zone

The *LC*-network impedance adjusting zone is determined by the relationship between. the impedance correction and the required capacitor's adjusting range for the *LC* network.in Fig.9. As the .impedance transformation needs to be done in two steps, the intermediate impedance $Z_{intermediate}$ is first defined that is .required to ..an arbitrary load-admittance $Y_{load} = G_{load} + jB_{load}$ to the required $Z_{match} = R_{match} + jX_{match}$. For. this reason the parallel section converts the Y_{load} to a transitional impedance, whose. real-part $R_{intermediate}$ should be .equal to the .matched .resistance R_{match}. Using (34) and (39) and rewriting define $R_{intermediate}$ as

$$R_{intermediate} = R_{match} = \frac{(G_{load})^2 + (B_{load} + B_{series} + B_{parallel})^2}{G_{load}} \tag{45}$$

Similarly, from Eqn. (42), the imaginary-part of. this intermediate.impedance.is given by

$$X_{intermediate} = R_{match}\sqrt{\frac{R_{match} + G_{load}}{R_{match}G_{load} + 1}} \tag{46}$$

and the corresponding intermediate susceptance is given by

$$B_{intermediate} = G_{load}\sqrt{\frac{R_{match} + G_{load}}{R_{match}G_{load} + 1}} \tag{47}$$

From. Eqn. (34), the required. parallel capacitor. $C_{parallel}$ is. given. by.

$$C_{parallel} = \frac{4\pi f}{2\pi f(B_{intermediate} - B_{load} + B_{L_{parallel}})} \tag{48}$$

Eqns. (45) and (46) define $C_{parallel}$ that. .is. needed to realise a desired .correction .from .a .load $G_{load} + jB_{load}$ to a .matched resistance R_{match} at frequency. f and parallel inductor susceptance $B_{L_{parallel}}$. Eqn. (24) can be rewritten to give the required magnitude of capacitance expressed as

$$C_{series} = 2\pi f(X_{intermediate} + X_{match} + X_{L_{series}}) \tag{49}$$

Eqns. (45) and (46).define the .series .capacitance C_{series} that. is. required to correct from a load $G_{load} + jB_{load}$ to. a matched. resistance R_{match} and. a matched reactance X_{match} at a frequency f and known inductor reactance $X_{L_{series}}$. It should be noted that C_{series} is independent of load susceptance. Furthermore, to realise a physically realizable solution, these two formulations are valid when.the series and parallel capacitors and the.square-root argument are positive. The last one is met for

$$R_{match} < 1/G_{load} \tag{50}$$

which. represents the impedance down-converting properties. of this *LC* network. For real-to-real impedance conversion, this transformation can only be descending, which outlines the impedance adjusting zone. The boundary condition for the up-converting LC network in Fig.10 is obtained when

$$B_{L_{parallel}} < B_{intermediate} + B_{load} \quad (51)$$

and. $$X_{L_{series}} < X_{intermediate} - X_{match} \quad (52)$$

Impedance adjusting range is bounded by fixed inductors $L_{parallel}$ and L_{series}. Susceptance of the parallel inductor sets the correction limit of the capacitive mismatch, and the reactance of the series inductor sets the correction limit of the capacitive intermediate impedances.

Capacitance ratios to transform an arbitrary load admittance $Y_{load} = G_{load} + jB_{load}$ to a required matched impedance Z_{match} needs to be determined. To do this the network should be able to adjust load admittance $Y_{load1} = G_{load1} + jB_{load1}$ to match with impedance Z_{match1} with a real-part R_{match1}, at a given frequency f_1, by a .parallel capacitance $C_{parallel1}$ and a. series. capacitance $C_{series1}$. Furthermore, the same network must be able to tune a load admittance. $Y_{load2} = G_{load2} + jB_{load2}$ to. Z_{match2} with resistance. R_{match2}, at a frequency f_2, by capacitance $C_{parallel2}$ and a series. capacitance $C_{series2}$. From Eqn. (46), the required capacitance adjusting zone of $C_{Z_{C_{parallel}}}$, given. by the capacitor ratio, can be expressed as

$$C_{Z_{C_{parallel}}} = \frac{f_1}{f_2}\left\{\frac{B_{intermediate2}+B_{load2}+B_{L_{parallel2}}}{B_{intermediate1}-B_{load1}-B_{L_{parallel1}}}\right\} \quad (53)$$

and, similarly, from Eqn. (47), for the series capacitor as

$$C_{Z_{C_{series}}} = \frac{f_1}{f_2}\left\{\frac{X_{intermediate1}+X_{match1}+X_{L_{series1}}}{X_{intermediate2}-X_{match2}-X_{L_{series2}}}\right\} \quad (54)$$

The above equations yield four solutions at the two frequencies (f_1 and f_2). This is because we can realise matching by transforming. the inductive. or capacitive intermediate. impedance. In addition, the equations reveal the capacitance ratio. is proportional to the frequency range of operation.

VI. Insertion Loss

The improvement in output power resulting from adaptive impedance matching is eroded by the insertion-loss of the matching network. In the case of parallel elements in the LC-network the loss is equivalent to the ratio between its loss and load conductance; and in the case for series elements, the loss is equivalent to the ratio between its loss and load resistance. A more accurate expression of loss is given by [2]

$$IL = 10.\log\left(1 + G_{load}\left(\frac{Q_{C_{parallel}}}{\left|B_{C_{parallel}}\right|} + \frac{Q_{L_{parallel}}}{\left|B_{L_{parallel}}\right|}\right) + R_{match}\left(\frac{Q_{C_{series}}}{\left|X_{C_{series}}\right|} + \frac{Q_{L_{series}}}{\left|X_{L_{series}}\right|}\right)\right) \quad (55)$$

The above expressions reveal the insertion-loss is a function of the impedance transformation step, as well as the component. values. used. to realise the transformation. To achieve a minimum loss, the susceptance of the parallel elements. and the reactance. of the series. elements must be small.

VII. State-of-the-Art IMNs Comparison

In this section, the characteristics of the proposed impedance matching network (IMN) has been mentioned and compared with the recent State-of-the-Art literature. The results are summarized in Table I, which illustrates that, the novelty of the propose work is: (i) automated tuning of LC impedance matching network to compensate for antenna mismatch with the RF-front-end; (ii) use of a tuning algorithm that converges to a matching point without the need of complex mathematical modeling of the system and nonlinear control components (varactor-diode) are taken into account to realise rapid convergence of impedance matching; (iii) varactor-diodes with any range of capacitance are applicable, (iv) employs digital circuitry for timing generation and simple analogue components; (v) reliable convergence is realized inside the tuning range of the LC network; (vi) reduces insertion-loss by using matching network elements to monitor voltage/current signals; and, (vii) enables autonomous control of adaptive antenna matching networks for optimum power transfer.

VIII. Conclusions

Adaptive impedance matching technique is proposed that controls reactive elements in an LC network for automatic compensation of fluctuations in antenna impedance. By cascading the two control loops we can achieve independent control of the real. and the imaginary-parts of the antenna impedance for fast convergence. Appropriate range of the capacitances was investigated for the varactor diodes as well as a useful way to realise improvement. in the mismatch by employing available varactor diodes. Prior to integration of the proposed technique in mobile wireless systems consideration will need to be given on how the impedance matching improvement is offset by loss introduced by its implementation.

Acknowledgments

This work is partially supported by RTI2018-095499-B-C31, Funded by Ministerio de Ciencia, Innovación y Universidades, Gobierno de España (MCIU/AEI/FEDER,UE), and innovation programme under grant agreement H2020-MSCA-ITN-2016 SECRET-722424 and the financial support from the UK Engineering and Physical Sciences Research Council (EPSRC) under grant EP/E022936/1.

TABLE I. STATE-OF-THE-ART IMNS COMPARISON

Refs.	Methodology	Impedance Type	Structure	Implementation	Bandwidth	Notes
[2]	Numerical	Insertion Loss	Flexible	Combination	Narrow	Complex control system, automated tuning, simple analogue components, complex mathematical modeling
[4]	Analytical	Single	Flexible	Combination	Wide	alleviated method, linear control components, simple analogue components, automated tuning
[15]	Numerical	Single	Fixed	Passive	Narrow	Complex mathematical modeling, alleviated method, complex control system
[16]	Numerical	Single	Fixed	Passive	Narrow	Transformers used, complex control system, expensive transformers, nonlinear control components
[17]	Analytical	Insertion Loss	Fixed	Combination	Narrow	Complex control system, nonlinear control components, transformers used
[18]	Analytical	Insertion Loss	Fixed	Passive	Wide	Alleviated method, complex mathematical modeling, heavy and expensive transformers
[19]	Analytical	Single	Fixed	Combination	Narrow	Transformers used, alleviated method
[20]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Bulky, heavy and expensive transformers
[21]	Numerical	Single	Flexible	Passive	Wide	Complex control system, nonlinear control components
[22]	Analytical	Single	Flexible	Combination	Narrow	Control system not discussed
[23]	Analytical	Single	Flexible	Combination	Narrow/Wide	Transformers used, Complex control system, nonlinear control components
[24]	Analytical	Single	Fixed	Combination	Narrow	Complex control system, alleviated method
[25]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Bulky, heavy and expensive transformers
[26]	Numerical	Insertion Loss	Fixed	Passive	Narrow	Transformers used, complex control system, expensive transformers, nonlinear control components
[27]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Alleviated method, complex control system, expensive transformers
[28]	Analytical	Insertion Loss	Fixed	Combination	Narrow	Transformers used, bulky, complex control system, expensive transformers
[29]	Numerical	Insertion Loss	Fixed	Combination	Narrow	Alleviated method, complex mathematical modeling, expensive transformers
[30]	Numerical	Insertion Loss	Flexible	Passive	Narrow	Complex control system, nonlinear control components, transformers used
[31]	Analytical	Insertion Loss	Fixed	Passive	Wide	Alleviated method, transformers used, nonlinear control components, complex control system
[32]	Analytical	Single	Fixed	Combination	Wide	Fully integrated, tuning for load (antenna) matching, nonlinear control components
[33]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Alleviated method, complex control system, fast operating speed, low development cost
[34]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Transformers used, alleviated method, complex control system, nonlinear control components
[35]	Analytical	Insertion Loss	Flexible	Combination	Narrow	Fully integrated, complex control system, expensive transformers, nonlinear control components
[36]	Analytical	Insertion Loss	Flexible	Combination	Wide	Transformers used, fully integrated, nonlinear control components, complex mathematical modeling
This work	Numerical	Insertion Loss	Flexible	Combination	Wide	Automated tuning, no need of complex mathematical modeling, linear control components, digital circuitry, simple analogue components, reliable convergence, reduction in insertion-loss, autonomous control of adaptive antenna matching networks, optimum power transfer, fully integrated

Combination: Passive and Active

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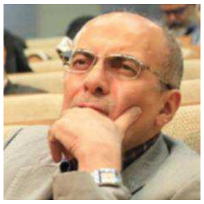

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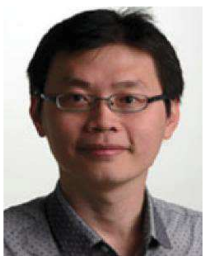

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Regarding teaching activities, Ernesto Limiti teaches, over his istitutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, "Elettronica per lo Spazio" within the Master Course in Sistemi Avanzati di Comunicazione e Navigazione Satellitare. He is a member of the committee of the PhD program in Telecommunications and Microelectronics at the University of Roma Tor Vergata, tutoring an average of four PhD candidates per year.

1) What is the problem being addressed by the manuscript and why is it important to the IEEE TMTT community?

The demand for the higher data rate has necessitated the development new generation of mobile communication systems. Antennas interface the mobile communications devices to the transmission medium and their performance is affected by the environment such as the human body and/or other objects in its proximity. The environment can adversely affect the antenna impedance resulting in a mismatch with input of the RF front end [1-3]. This paper describes an effective adaptive antenna impedance matching control algorithm which has two cascaded control loops to independently control the impedance's real- and imaginary-parts. Voltage and current are monitored in the matching network to reliably control the impedance and thereby reduce insertion-loss (IL). In addition, the proposed technique operates autonomously.

2) What is the novelty of your work over the existing work?

The proposed technique uses a tuning algorithm that converges to a matching point and does not require complex mathematical modelling of the system including its nonlinear control components. The system employs digital circuitry to generate the timing signal and simple analogue components. It is shown reliable convergence is realised inside the LC network's tuning range. Furthermore, insertion-loss was minimised by using matching network components to monitor the voltage/current signals. The proposed technique enables autonomous control of adaptive antenna matching networks for optimum power transfer.

3) Provide up to three references, published or under review, (journal papers, conference papers, technical reports, etc.) done by the authors/coauthors that are closest to the present work. Upload them as supporting documents if they are under review or not available in the public domain. Enter "N.A." if it is not applicable.

[4] M. Alibakhshikenari, B. S. Virdee, C. H. See, R. A. Abd-Alhameed, F. Falcone, E. Limiti, "Automated Reconfigurable Antenna Impedance for Optimum Power Transfer," 2019 IEEE Asia-Pacific Microwave Conference (APMC), pp.1461-1463.

4) Provide up to three references (journal papers, conference papers, technical reports, etc.) done by other authors that are most important to the present work. Enter "N.A." if it is not applicable.

This is an extension of Ref. [2]. Additionally, we have provided a comparison section to comparing the proposed work with the recent and related literature focusing on the adaptive impedance matching techniques, which have been presented in Refs. [15-36].

The novelty of the propose work is: (i) automated tuning of LC impedance matching network to compensate for antenna mismatch with the RF-front-end; (ii) use of a tuning algorithm that converges to a matching point without the need of complex mathematical modeling of the system and nonlinear control components (varactor-diode) are taken into account to realise rapid convergence of impedance matching; (iii) varactor-diodes with any range of capacitance are applicable, (iv) employs digital circuitry for timing generation and simple analogue components; (v) reliable convergence is realized inside the tuning range of the LC network; (vi) reduces insertion-loss by using matching network elements to monitor voltage/current signals; and, (vii) enables autonomous control of adaptive antenna matching networks for optimum power transfer.

Optimum Power Transfer in RF-Front-End Systems Using Adaptive Impedance Matching Technique

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***Abstract*- Matching the antenna's impedance with the RF-front-end is an issue for optimum power transfer, which affects radiation efficiency. This paper describes a technique for automatically tuning an *LC* impedance matching network to compensate for antenna mismatch with the RF-front-end. The technique converges to a matching point and does not require complex mathematical modelling of the system comprising non-linear control components. The system implementing the technique employs digital circuitry for synchronization and to realize relatively simple analogue circuits. Reliable convergence is realised inside the adjusting range of the *LC* network using a couple of control-loops whose purpose is to independently control the *LC* impedance. The systems insertion-loss is reduced by using matching network components that monitor the voltage/current variations. The technique enables autonomous control of adaptive antenna matching networks for optimum power transfer.**

***Keywords*- *LC* impedance matching network (IMN), optimum power transfer, antenna impedance, RF-front-end transceiver, simple analogue circuits, couple of control-loops.**

I. Introduction

The demand for the higher data rate has necessitated the development new generation of mobile communication systems. Antennas interface the mobile communications devices to the transmission medium and their performance is affected by the environment such as the human body and/or other objects in its proximity. The environment can adversely affect the antenna's impedance resulting in unwanted mismatch at the input of the RF-front-end [1]-[3]. In the transmission-mode and under the worst-case scenario the mismatch in the impedance can adversely affect the power-amplifier performance resulting from reflected power, which is likely to reduce the life of the battery due to excessive energy consumption [4]. In the receive mode, the carrier-to-noise ratio is degraded.

To resolve the issue with impedance mismatch, isolators can be used however they can undermine the maximum radiated power and efficiency. In addition, isolators have a narrow bandwidth and therefore are unsuitable for multiband phones. Alternatively, the quality of the link can be maintained by applying adaptive impedance matching techniques [5],[6]. This technique is popular for maintaining system performance parameters, i.e. optimum radiated power, linearity of power-amplifier, sensitivity of receiver, and power-efficiency. Moreover, its applicable for wireless systems operating at multiple bands as it enables a single impedance matching network (IMN) to suffice. However, the use of adaptive IMN in wireless systems are incumbered by stringent criteria on insertion-loss (*IL*), degree of linearity, and tuning span. The use of adaptively controlled IMNs [7],[8] is only possible with the availability of highly linear and high Quality-factor tuneable components such as RF microelectromechanical (MEM) devices [9],[10], CMOS-switches [11],[12], silicon and Barium-Strontium-Titanate (BST) varactor diodes [13],[14].

Recent works reported in literature on adaptive impedance-matching include: (i) a T-shaped adaptive impedance matching system that refers to predetermined load-Q information for different matching conditions to implement the impedance matching [15]. Here the T-shaped network uses tuneable capacitors that are controlled by digital relays. The frequency range for tuning is limited to between 10-95 MHz; (ii) the use of fuzzy inference system to construct the mapping relationship between load impedance and the matched capacitor set [16]. This technique is applied to optimise power transfer between coupled coils at a fixed frequency; (iii) the use of a machine learning strategy based on neural networks for the real-time range-adaptive automatic impedance matching of wireless power transfer applications [17]. Here the voltage controlled variable capacitors are employed in a π-type matching circuit. The matching is implemented for different gap spacing between the transmitter and receiver coils at a fixed frequency; and (iv) using RF MEMS based on a coplanar waveguide based on suspended bridges for impedance tuning [18]. The tuning is controlled by a variable applied DC voltage to the bridges over 1-6 GHz.

This paper describes an effective adaptive antenna impedance matching control algorithm. The IMN includes a couple of control-loops for independently controlling the impedance. It senses the voltage/current in the matching network to reliably control the real and imaginary parts of impedance and thereby reduce *IL*. In addition, the proposed technique operates autonomously.

Rest of the paper has been organized as follow as. The proposed approach to control antenna-impedance matching has been described in Section II. Section III presents controlling antenna-impedance matching based on LC network, which has been divided to two sub-sections of (i) series LC network, and (ii) parallel LC network. Adaptive control of parallel LC network has been illustrated in Section IV. Next section explains the LC-network adjusting zone. The Insertion loss has been presented in Section VI. Finally the paper has been concluded in the last Section VII.

II. Proposed Approach to Control Antenna-Impedance Matching

The proposed configuration of the adaptive matching system is depicted in Fig.1. In the transmit mode it consists of a matching network, directional coupler for mismatch measurement, a switch, switching timing generator, and time constant generator. Varactor diodes in the matching network provide electronically controllable capacitance. The system uses the magnitude of the return-loss (Γ) that is measured between the RF-source and the matching circuit input for impedance matching. As information on the Γ phase is also essential to minimize the degree of mismatch the system uses a test signal to determine whether the mismatch increases or decreases. This information is used to precisely control the capacitance in the matching network.

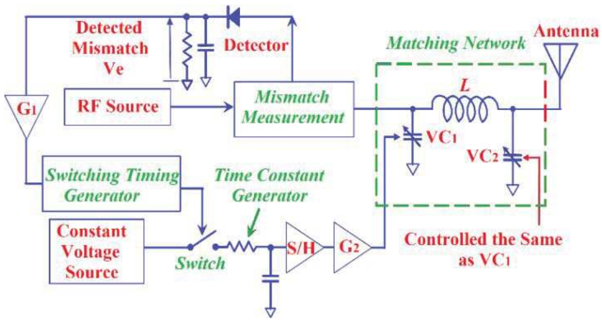


Fig.1.Configuration of the proposed adaptive matching system.

Protocol used here for adaptively matching involves measuring the degree of mismatch with the detection circuitry. This is achieved by turning the switch 'on' to increase the control voltage to the varactor#1 (VC_1). If the mismatch worsens the system acknowledges this and turns the switch 'off'. If the mismatch reduces the system acknowledges this by keeping the switch 'on'. This is maintained for the period of the control frame for VC_1. In the time frame period of VC_1, the control voltage to the varactor#2 (VC_2) is maintained at the value of the last time frame of the VC_2. The voltage is maintained using the sample-and-hold circuitry. At the end of the time frame period of VC_1, the control voltage for VC_1 is maintained and the time frame period commences for VC_2. Compared to other conventional techniques that use the steepest descent algorithm for optimization, the merits of the proposed system are: (i) no need for complex mathematical modelling; (ii) the nonlinearity of the control elements (varactor-diode) are taken into account to realise rapid convergence of impedance matching; and (iii) varactor-diodes with any range of capacitance are applicable. As it is not possible to obtain a desired varactor-diode with the required capacitance range the only option therefore is to use an available varactor-diode with a broader capacitance range. In the system an appropriate inductance L needs to be chosen, which is determined by simulation through parametric analysis. To characterise the improvement in impedance mismatch time characteristics of the return-loss between the matching network and the RF-front-end was used.

III. Controlling Antenna-Impedance Matching Based on *LC* Network

In the proposed technique the *LC*-network is extended in comparison to Ref. [2] to include two loops comprising a serial *LC* sub-loop and a parallel *LC* sub-loop that are independent from each other, as shown in Fig.2. These loops can now control components constituting the impedance matching network. The control loops essentially convert an undefined load admittance Y_{load} to the required matching impedance Z_{match} represented by [2]

$$Z_{match} = R_{match} + j\,X_{match} \quad (1)$$

The loop#1 controls the parallel and series capacitors $C_{parallel_1}$ and C_{series_2}, respectively, constituting the imaginary-part of the match impedance X_{match}. The loop#2 controls the parallel and series capacitors $C_{parallel_3}$ and C_{series_4}, respectively, to set R_{match}. R_{match} is the real-part of the match impedance. The intermediate impedance ($Z_{intermediate}$) is given by [2]

$$Z_{intermediate} = R_{intermediate} + j\,X_{intermediate} \quad (2)$$

If loop#2 is frozen and the amplifier-gain .errors A_{error_3} and A_{error_4} become significant, the signal errors S_{error_3} and S_{error_4} will be insignificant.

$$R_{intermediate} = 1 + \frac{R_{ref2}}{K_{dr2}} \quad (3)$$

Where R_{ref2} and K_{dr2} are the magnitude of the reference and the detector constant, respectively, of loop#2 setting R_{match}. Loop#2 introduces an intermediate reactance defined by

$$X_{intermediate} = \frac{K_{dx2}}{X_{ref2}} - 1 \quad (4)$$

Where X_{ref2} and K_{dx2} are the magnitude of the reference and the detector constant, respectively, of loop#2 setting X_{match}. Similarly, if loop#1 is frozen and the amplifier-gain errors A_{error_1} and A_{error_2} are significant, the signal errors S_{error_1} and S_{error_2} will be insignificant .and, .by .approximation, .hold .true

$$R_{match} = 2 + \frac{R_{ref1}}{K_{dr1}} + \frac{R_{ref2}}{K_{dr2}} \quad (5)$$

Where R_{ref1} and K_{dr1} are the magnitude of the reference and the detector constant, respectively, of loop#1 setting R_{match}. Loop#1 introduces .an intermediate reactance X_{match} defined by

$$X_{match} = \frac{K_{dx1}}{X_{ref1}} + \frac{K_{dx2}}{X_{ref2}} \quad (6)$$

Where X_{ref1} and K_{dx1} are the reference value and the detector constant, respectively, of the first loop setting X_{match}. From Eqn. (1) Z_{match} can be written as

$$Z_{match} = 2 + \frac{R_{ref1}}{K_{dr1}} + \frac{R_{ref2}}{K_{dr2}} + j\left(\frac{K_{dx1}}{X_{ref1}} + \frac{K_{dx2}}{X_{ref2}}\right) \quad (7)$$

Eqn. (7) confirms the matched impedance is not dependent.of Y_{load}, the amplifier gain errors, and. the magnitude of the matching-network .components.

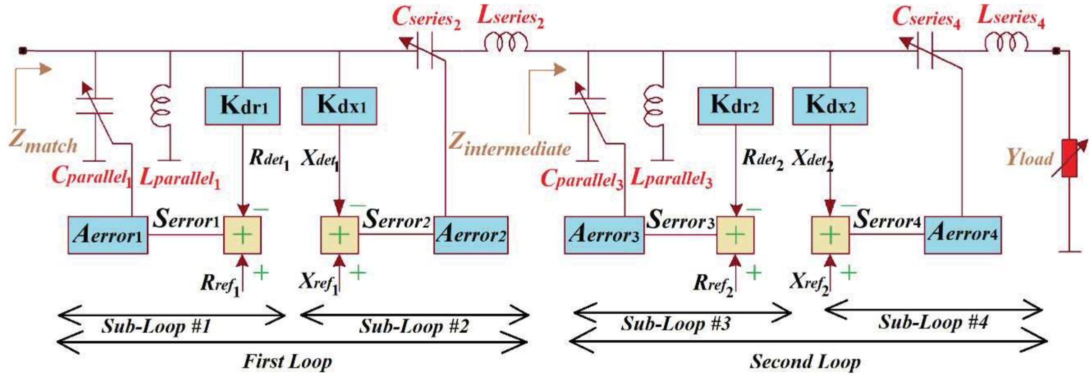
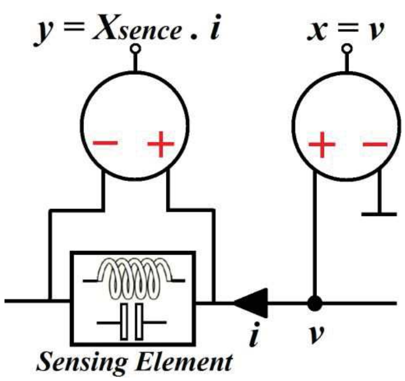


Fig.2. Schematic diagram for independent control of the matched impedance Z_{match} of an LC network.

Monitoring impedance. mismatch involves monitoring of RF signal and converting it to. *dc*. As the impedance is a function of voltage and current, the RF voltage. and RF current. can be sensed to establish the impedance. Fig.3 shows the point of voltage measurement *"v"* and differential. voltage. across a. monitoring component is used to measure the current. *"i"* and hence its reactance. X_{sense} can be determined. The monitoring component can be either an inductance or. capacitance that .is part of the tuneable IMN. The impedance at the node Z is determined by taking the ratio between the outputs of the two buffer-amplifiers in Fig.3.



$$Z = \frac{x}{y} X_{sense} \quad (8)$$
$$Y = \frac{y}{x} \frac{1}{X_{sense}} \quad (9)$$

Fig.3. Impedance Z or admittance Y can be deduced by sensing the voltage "*v*" and current "*i*".

Individual components representing the impedance can be determined from the *RF* signals. '*x*' and *'y'* using the detector. configuration shown in Fig.4. Impedance detection requires applying voltage information to input *'x'*

$$x = A_x \cos(\omega.t + \theta_x) \quad (10)$$

and current information.to input *"y"*

$$y = A_y \cos(\omega.t + \theta_y).\left|\frac{1}{X_{sense}}\right|.\, e^{j\frac{\pi}{4}} (11)$$

Input signal *'x'* is fed the first three mixers, i.e. to *mixer* #1 with 90° shifted in phase, to *mixer* #2 with a limited amplitude, and to *mixer* #3. Whereas input signal *'y'* is fed to the same mixers with 90° shifted in phase and is also applied to *mixer* #4 with limited amplitude to generate cosine and sine terms of the phase difference between *'x'* and *'y'*, both corresponding to magnitudes A_x and A_y. *Mixers* 1 & 2, and *mixers* 3 & 4 are used to find the magnitudes A_x and A_y of input signals *'x'* and *'y'*, respectively. The output signal of *mixers* #1 & #2 is split by the output signal of *mixers* #3 & #4 and vice versa to obtain the detected impedance Z_{detect}, represented by

$$Z_{detect} = R_{detect} + jX_{detect} \quad (12)$$

where
$$R_{detect} = \frac{a \times b}{d} \quad (13)$$
$$X_{detect} = \frac{c \times d}{a} \quad (14)$$
$$\theta_{detect} = \theta_x - \theta_y \quad (15)$$

where *a*, *b*, *c*, and *d* are defined as

$$a = 2\pi A_x \cos(\theta_{detect}).\frac{1}{X_{sense}} \quad (16)$$
$$b = \frac{\pi}{2} A_x \sin(\theta_{detect}) \quad (17)$$
$$c = \pi A_y \cos(\theta_{detect}) \quad (18)$$
$$d = \frac{\pi}{2} A_y \sin(\theta_{detect}).\frac{1}{X_{sense}} \quad (19)$$

From Eqn.(16)-(19), the real and imaginary parts of the detected impedance are specified as follow as:

$$R_{detect} = \frac{2\pi A_x^2 \cos(\theta_{detect}) \sin(\theta_{detect})}{A_y \sin(\theta_{detect})} \quad (20)$$

$$X_{detect} = \frac{\pi A_y^2 \cos(\theta_{detect}) \sin(\theta_{detect})}{4 A_x \cos(\theta_{detect})} \quad (21)$$

By combining Eqns. (20) and (21) the impedance detected is given by

$$Z_{detect} = \frac{2\pi A_x^2 \cos(\theta_{detect}) \sin(\theta_{detect})}{A_y \sin(\theta_{detect})} + j\frac{\pi A_y^2 \cos(\theta_{detect}) \sin(\theta_{detect})}{4 A_x \cos(\theta_{detect})} \quad (22)$$

According to Eqns. (20) and (21), the detected values of the impedance are independent of the frequency. This means frequency compensation is not required for high accuracy across a wideband frequency. The detected values of the impedance are related .to the ratios $\frac{A_x}{A_y}$ and $\frac{A_y}{A_x}$, hence they are.

independent. of the power of the *RF* signal transmitted. Moreover, according.to Eqn. (15), θ_{detect} is the differential phase difference between θ_x and θ_y.

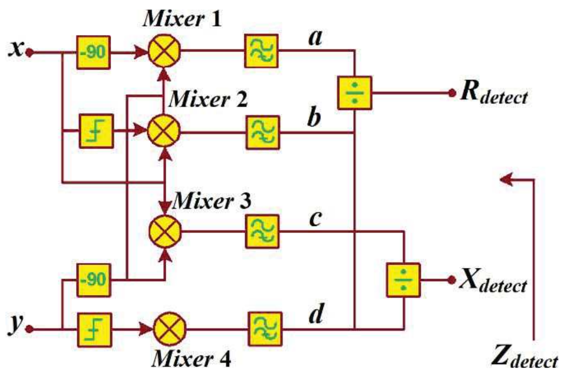


Fig.4. Quadrature detector that generates the constituent parts of the detected impedance from the return-loss.

By simply exchanging the detector input signals *'x'* and *'y'* the detector. generates the real-. and imaginary-parts of the admittance. When input signals *'x'* and *'y'* represent. the reflected and incident power, the detector generates a reading. of return-loss (*Γ*). The accuracy of the detector over a wide output power range, which is essentially dependent on limiter. and its amplitude. dependent. phase-delay, is traded-off. against power. consumption. The detector needs to be operated at a lower 'on/off' duty-cycle (<1%) to conserve power since the settling time of the detector is normally short (10-100 □s) compared. to the impedance variation of the antenna. The detector is susceptible to receiving unwanted signals as it's not frequency selective. These signals can cause the direction of the energy flow to change when they are stronger than the transmit signal. In that case the detector. reads the network. impedance. seen into the reverse. direction. However, at lower output. power (<0.dBm), there is no advantage from .adaptive .impedance .matching, and the .detector .can .be .turned . 'off' to prevent erroneous control.

A. Series LC Network

In Fig.5, the matched impedance Z_{match} of a series *LC* network represents the tuneable network of the sub-loops 3 and 4 of the first and second loops, respectively, in Fig.2, and is given by

$$Z_{match} = R_{match} + jX_{match} \qquad (23)$$

in which the matched reactance X_{match} is given by

$$X_{match} = X_{L_{series}} + X_{C_{series}} + X_{load} \qquad (24)$$

where

$$X_{L_{series}} = X_{L_{series\,2}} + X_{L_{series\,4}} \qquad (25)$$

and

$$X_{C_{series}} = X_{C_{series\,2}} + X_{C_{series\,4}} \qquad (26)$$

and the matched resistance R_{match} is

$$R_{match} = R_{load} \qquad (27)$$

Tuning the series capacitor values C_{series} affects X_{match}, which is a function of tuning reactance ($X_{C_{series}}$), whereas. the matched. series. resistance (R_{match}) .is equivalent to load resistance. (R_{load}). In adaptive. matching. .networks, the orthogonal property of .resistance and .reactance is exploited in the .adaptive *LC* network to modify the matched .reactance (X_{match}) to the required .value .without .affecting the .matched .resistance (R_{match}).

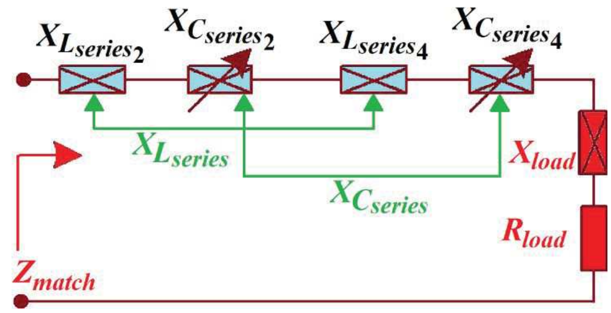


Fig.5. Adjustable *LC* network to provide the required inductive and capacitive load reactance.

The proposed series *LC* network is used to alter the real-part of the matched admittance. The matched impedance (Z_{match}) can be represented by matched admittance given by

$$Y_{match} = G_{match} + jB_{match} \qquad (28)$$

where $$G_{match} = \frac{(R_{load})^2 + (X_{match})^2}{R_{load}} \qquad (29)$$

and $$B_{match} = \frac{(R_{load})^2 + (X_{match})^2}{X_{match}} \qquad (30)$$

The matched conductance (G_{match}) is a .symmetric .function of X_{match} .with a maxima of $1/R_{load}$. Consequently, a .series *LC* network, shown in Fig.6, can only convert load resistance R_{load} to a conductance that is smaller than $1/R_{load}$. Two solutions. exist for. the condition $G_{match} < 1/R_{load}$ .given. by

$$X_{match} = \frac{R_{load}}{G_{match}}\sqrt{(1 + G_{match}R_{load})} \qquad (31)$$

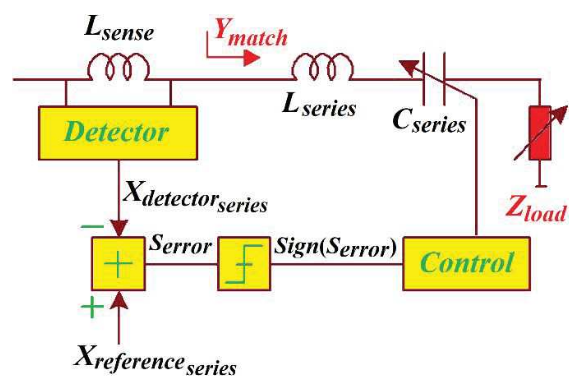


Fig.6. Series.*LC* network to control the real-part of the matched.admittance G_{match}.

Substitution of Eqn. (31) into (30) gives corresponding matched susceptance given by

$$B_{match} = \sqrt{\left(\frac{R_{load}}{G_{match}} + G_{match}R_{load}\right) + 1} \qquad (32)$$

B. Parallel LC Network

Fig.7 shows the matched admittance Y_{match} of a parallel LC network and representing the tuneable network of the sub-loops 1 and 3 of the first and second loops, respectively, (see Fig.2), is defined as

$$Y_{match} = G_{match} + jB_{match} \qquad (33)$$

Where

$$B_{match} = B_{L_{parallel}} + B_{C_{parallel}} + B_{load} \qquad (34)$$

$$B_{L_{parallel}} = B_{L_{parallel}\,1} + B_{L_{parallel}\,3} \qquad (35)$$

$$B_{C_{parallel}} = B_{C_{parallel}\,1} + B_{C_{parallel}\,3} \qquad (36)$$

and the matched conductance G_{match} is presented by

$$G_{match} = G_{load} \qquad (37)$$

Matching admittance (Y_{match}) of this parallel.LC-network corresponds. to. $Y_{intermediate}$ of the LC-network. The matched susceptance (B_{match}) is a function of tunable susceptance ($B_{C_{parallel}}$), .whereas the matched. conductance. G_{match} is equal .to load conductance G_{load} and independent $B_{C_{parallel}}$. Y_{match}($C_{parallel}$) and the orthogonal. property of conductance/susceptance can .be exploited for adaptive. control. of the IMN by tuning the matched susceptance to the required .value without adversely affecting the matched conductance.

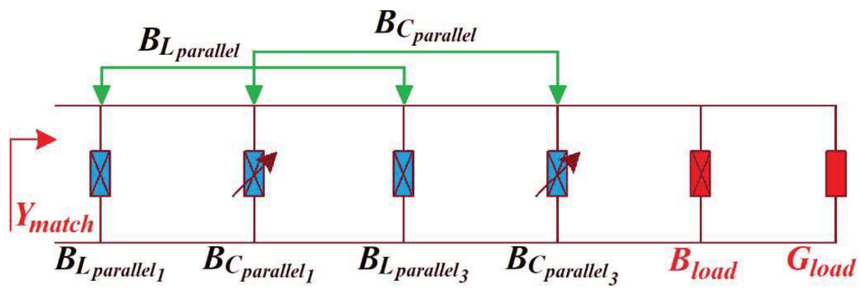


Fig.7. Variable parallel LC network and its matched admittance Y_{match}.

Moreover, the parallel LC network. allows control of the real-part of R_{match}. Matched admittance. (Y_{match}) can be represented by matched. impedance (Z_{match}) thus

$$Z_{match} = R_{match} + jX_{match} \qquad (38)$$

where
$$R_{match} = \frac{G_{load} + B_{match}}{(G_{load})^2} \qquad (39)$$

$$X_{match} = \frac{G_{load} + B_{match}}{(B_{match})^2} \qquad (40)$$

In Fig. 8, R_{match} is a.symmetric function. of B_{match} with a maxima of $1/R_{load}$. .

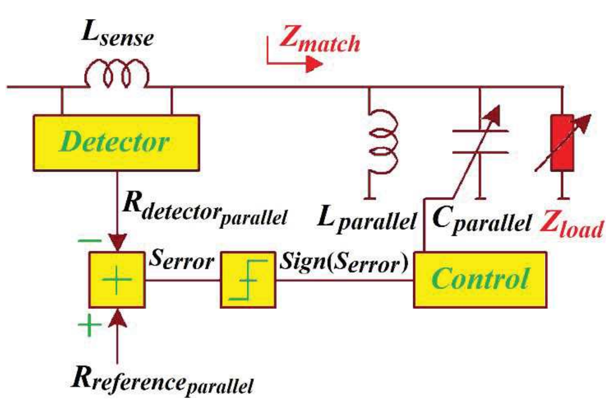


Fig.8. Parallel LC network to control the real-part of the matched impedance R_{match}.

Hence, a parallel. LC. network. can transform load conductance (G_{load}) to a .resistance that.is smaller than $1/R_{load}$. When $R_{match} < 1/G_{load}$, two solutions are obtained from Eqn. (39) and given by

$$B_{match} = \frac{R_{match}}{G_{load}}\sqrt{(1 + R_{match}G_{load})} \qquad (41)$$

Substitution of Eqns. (36) into (35) gives the two matched reactances

$$X_{match} = \frac{G_{load}}{R_{match}}\sqrt{(R_{match}G_{load}) + 1} \qquad (42)$$

IV. Adaptive Control of Parallel LC Network

The algorithm that was developed determined the convergence operation of the control loop. In fact, the tuneable capacitor, which is essentially a switched-capacitor array, is controlled by the sign of the error signal $SIGN(S_{error}$) generated from the series and parallel control loops. The up/down counter (U/D) is used to store the value of the control array. The output of the U/D is incremented or decremented in steps of one least significant bit, which depends on the error signal.

The convergence operation can be examined in open-loops conditions. At the controller when the loops (Figs. 6 and 8) are opened we sense $SIGN(S_{error})$ across the entire. ranges of X_{match} and B_{match}, SIGN(S_{error}) is +1. Hence, the directions of capacitor controls shown in Fig. 6 and 8 are not definitive. This can be resolved by using the detected.

information on. the signs .of .the .matched susceptance $SIGN(-B_{match})$ and the matched reactance $SIGN(-X_{match})$, respectively, as a secondary .control criterion. shown in Fig.9 by dotted green blocks. The secondary feedback path allows the series and parallel control. loops. Criteria to be determined by the two detection. thresholds. for each loops of $G_{match} = R_{reference_{series}}$ and $B_{match} = 0$ (for series control. loop shown in Fig.6) and $R_{match} = R_{reference_{parallel}}$ and $X_{match} = 0$ (for parallel control loop. shown in Fig.8). Assuming. that detector. constants K_{series} and $K_{parallel}$ are equated to one,. S_{error} is now represented by

$$S_{error_{series}} = SIGN(-B_{match})\ .\ R_{reference_{series}} - R_{detector_{series}} \quad (43)$$

$$S_{error_{parallel}} = SIGN(-X_{match})\ .\ R_{reference_{parallel}} - R_{detector_{parallel}} \quad (44)$$

As $R_{reference}$, R_{match} and G_{match} are always positive, error signal S_{error} becomes strongly negative when $SIGN(-X_{match})$ and $SIGN(-B_{match})$ are negative. Hence, $SIGN(S_{error})$ is now unambiguous, and the first and second loops converge .reliably .to .operating .over the .entire .range of B_{match} and X_{match}.

The impedance matching network characteristics are applied to create .an adaptive *LC* network. that comprises a pair of loops, as shown in Fig.9. Control loop#1 sets the real-part of R_{match}. The sensing inductor L_{sense} consists of the series *LC* network controlled by the both loops. The loop#2 transforms the matched reactance X_{match} to $X_{reference}$. In fact, no information. on the real-part of the matched impedance is required. This makes. $R_{detector}$ surplus to requirement. If X_{match} is controlled iteratively the sign of $X_{detector}$ is significant.

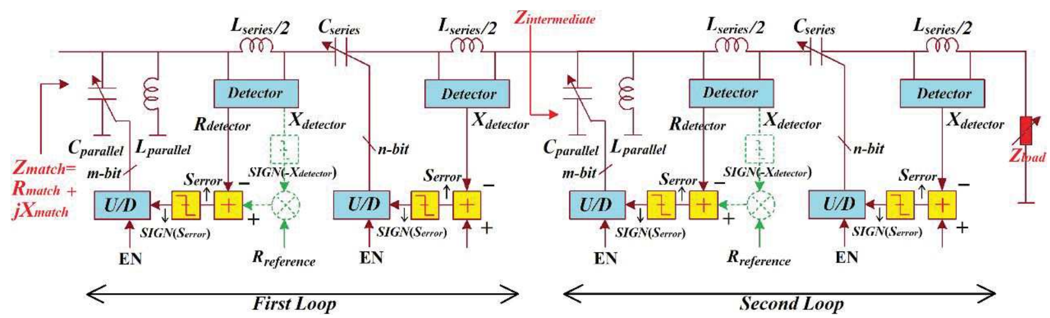


Fig.9. *LC* network implemented. An extra feedback path is shown in dotted 'green' blocks. This feedback ensures the first and second loops to function in their stable regions.

V. *LC*-Network Adjusting Zone

The *LC*-network impedance adjusting zone is determined by the relationship between. the impedance correction and the required capacitor's adjusting range for the *LC* network.in Fig.9. As the .impedance transformation needs to be done in two steps, the intermediate impedance $Z_{intermediate}$ is first defined that is .required to ..an arbitrary load-admittance $Y_{load} = G_{load} + jB_{load}$ to the required $Z_{match} = R_{match} + jX_{match}$. For. this reason the parallel section converts the Y_{load} to a transitional impedance, whose. real-part $R_{intermediate}$ should be .equal to the .matched .resistance R_{match}. Using (34) and (39) and rewriting define $R_{intermediate}$ as

$$R_{intermediate} = R_{match} = \frac{(G_{load})^2 + (B_{load} + B_{series} + B_{parallel})^2}{G_{load}} \quad (45)$$

Similarly, from Eqn. (42), the imaginary-part of. this intermediate.impedance.is given by

$$X_{intermediate} = R_{match}\sqrt{\frac{R_{match} + G_{load}}{R_{match}G_{load} + 1}} \quad (46)$$

and the corresponding intermediate susceptance is given by

$$B_{intermediate} = G_{load}\sqrt{\frac{R_{match} + G_{load}}{R_{match}G_{load} + 1}} \quad (47)$$

From. Eqn. (34), the required. parallel capacitor. $C_{parallel}$ is. given. by.

$$C_{parallel} = \frac{4\pi f}{2\pi f(B_{intermediate} - B_{load} + B_{L_{parallel}})} \quad (48)$$

Eqns. (45) and (46) define $C_{parallel}$ that. .is. needed to realise a desired .correction .from .a .load $G_{load} + jB_{load}$ to a .matched resistance R_{match} at frequency. f and parallel inductor susceptance $B_{L_{parallel}}$. Eqn. (24) can be rewritten to give the required magnitude of capacitance expressed as

$$C_{series} = 2\pi f(X_{intermediate} + X_{match} + X_{L_{series}}) \quad (49)$$

Eqns. (45) and (46).define the .series .capacitance C_{series} that. is. required to correct from a load $G_{load} + jB_{load}$ to. a matched. resistance R_{match} and. a matched reactance X_{match} at a frequency f and known inductor reactance $X_{L_{series}}$. It should be noted that C_{series} is independent of load susceptance. Furthermore, to realise a physically realizable solution, these two formulations are valid when.the series and parallel capacitors and the.square-root argument are positive. The last one is met for

$$R_{match} < {}^{1}/_{G_{load}} \quad (50)$$

which. represents the impedance down-converting properties. of this *LC* network. For real-to-real impedance conversion, this transformation can only be descending, which outlines the impedance adjusting zone. The boundary condition for the up-converting LC network in Fig.10 is obtained when

$$B_{L_{parallel}} < B_{intermediate} + B_{load} \qquad (51)$$

and. $X_{L_{series}} < X_{intermediate} - X_{match}$ (52)

Impedance adjusting range is bounded by fixed inductors $L_{parallel}$ and L_{series}. Susceptance of the parallel inductor sets the correction limit of the capacitive mismatch, and the reactance of the series inductor sets the correction limit of the capacitive intermediate impedances.

Capacitance ratios to transform an arbitrary load admittance $Y_{load} = G_{load} + jB_{load}$ to a required matched impedance Z_{match} needs to be determined. To do this the network should be able to adjust load admittance $Y_{load1} = G_{load1} + jB_{load1}$ to match with impedance Z_{match1} with a real-part R_{match1}, at a given frequency f_1, by a .parallel capacitance $C_{parallel1}$ and a. series. capacitance $C_{series1}$. Furthermore, the same network must be able to tune a load admittance. $Y_{load2} = G_{load2} + jB_{load2}$ to. Z_{match2} with resistance. R_{match2}, at a frequency f_2, by capacitance $C_{parallel2}$ and a series. capacitance $C_{series2}$. From Eqn. (46), the required capacitance adjusting zone of $C_{Z_{C_{parallel}}}$, given. by the capacitor ratio, can be expressed as

$$C_{Z_{C_{parallel}}} = \frac{f_1}{f_2}\left\{\frac{B_{intermediate2} + B_{load2} + B_{L_{parallel2}}}{B_{intermediate1} - B_{load1} - B_{L_{parallel1}}}\right\} \qquad (53)$$

and, similarly, from Eqn. (47), for the series capacitor as

$$C_{Z_{C_{series}}} = \frac{f_1}{f_2}\left\{\frac{X_{intermediate1} + X_{match1} + X_{L_{series1}}}{X_{intermediate2} - X_{match2} - X_{L_{series2}}}\right\} \qquad (54)$$

The above equations yield four solutions at the two frequencies (f_1 and f_2). This is because we can realise matching by transforming. the inductive. or capacitive intermediate. impedance. In addition, the equations reveal the capacitance ratio. is proportional to the frequency range of operation.

VI. Insertion Loss

The improvement in output power resulting from adaptive impedance matching is eroded by the insertion-loss of the matching network. In the case of parallel elements in the LC-network the loss is equivalent to the ratio between its loss and load conductance; and in the case for series elements, the loss is equivalent to the ratio between its loss and load resistance. A more accurate expression of loss is given by [2]

$$IL = 10.\log\left(1 + G_{load}\left(\frac{Q_{C_{parallel}}}{|B_{C_{parallel}}|} + \frac{Q_{L_{parallel}}}{|B_{L_{parallel}}|}\right) + R_{match}\left(\frac{Q_{C_{series}}}{|X_{C_{series}}|} + \frac{Q_{L_{series}}}{|X_{L_{series}}|}\right)\right) \qquad (55)$$

The above expressions reveal the insertion-loss is a function of the impedance transformation step, as well as the component. values. used. to realise the transformation. To achieve a minimum loss, the susceptance of the parallel elements. and the reactance. of the series. elements must be small.

VII. State-of-the-Art IMNs Comparison

In this section, the characteristics of the proposed impedance matching network (IMN) has been mentioned and compared with the recent State-of-the-Art literature. The results are summarized in Table I, which illustrates that, the novelty of the propose work is: (i) automated tuning of LC impedance matching network to compensate for antenna mismatch with the RF-front-end; (ii) use of a tuning algorithm that converges to a matching point without the need of complex mathematical modeling of the system and nonlinear control components (varactor-diode) are taken into account to realise rapid convergence of impedance matching; (iii) varactor-diodes with any range of capacitance are applicable, (iv) employs digital circuitry for timing generation and simple analogue components; (v) reliable convergence is realized inside the tuning range of the LC network; (vi) reduces insertion-loss by using matching network elements to monitor voltage/current signals; and, (vii) enables autonomous control of adaptive antenna matching networks for optimum power transfer.

VIII. Conclusions

Adaptive impedance matching technique is proposed that controls reactive elements in an LC network for automatic compensation of fluctuations in antenna impedance. By cascading the two control loops we can achieve independent control of the real. and the imaginary-parts of the antenna impedance for fast convergence. Appropriate range of the capacitances was investigated for the varactor diodes as well as a useful way to realise improvement. in the mismatch by employing available varactor diodes. Prior to integration of the proposed technique in mobile wireless systems consideration will need to be given on how the impedance matching improvement is offset by loss introduced by its implementation.

Acknowledgments

This work is partially supported by RTI2018-095499-B-C31, Funded by Ministerio de Ciencia, Innovación y Universidades, Gobierno de España (MCIU/AEI/FEDER,UE), and innovation programme under grant agreement H2020-MSCA-ITN-2016 SECRET-722424 and the financial support from the UK Engineering and Physical Sciences Research Council (EPSRC) under grant EP/E022936/1.

TABLE I. STATE-OF-THE-ART IMNS COMPARISON

Refs.	Methodology	Impedance Type	Structure	Implementation	Bandwidth	Notes
[2]	Numerical	Insertion Loss	Flexible	Combination	Narrow	Complex control system, automated tuning, simple analogue components, complex mathematical modeling
[4]	Analytical	Single	Flexible	Combination	Wide	alleviated method, linear control components, simple analogue components, automated tuning
[15]	Numerical	Single	Fixed	Passive	Narrow	Complex mathematical modeling, alleviated method, complex control system
[16]	Numerical	Single	Fixed	Passive	Narrow	Transformers used, complex control system, expensive transformers, nonlinear control components
[17]	Analytical	Insertion Loss	Fixed	Combination	Narrow	Complex control system, nonlinear control components, transformers used
[18]	Analytical	Insertion Loss	Fixed	Passive	Wide	Alleviated method, complex mathematical modeling, heavy and expensive transformers
[19]	Analytical	Single	Fixed	Combination	Narrow	Transformers used, alleviated method
[20]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Bulky, heavy and expensive transformers
[21]	Numerical	Single	Flexible	Passive	Wide	Complex control system, nonlinear control components
[22]	Analytical	Single	Flexible	Combination	Narrow	Control system not discussed
[23]	Analytical	Single	Flexible	Combination	Narrow/Wide	Transformers used, Complex control system, nonlinear control components
[24]	Analytical	Single	Fixed	Combination	Narrow	Complex control system, alleviated method
[25]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Bulky, heavy and expensive transformers
[26]	Numerical	Insertion Loss	Fixed	Passive	Narrow	Transformers used, complex control system, expensive transformers, nonlinear control components
[27]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Alleviated method, complex control system, expensive transformers
[28]	Analytical	Insertion Loss	Fixed	Combination	Narrow	Transformers used, bulky, complex control system, expensive transformers
[29]	Numerical	Insertion Loss	Fixed	Combination	Narrow	Alleviated method, complex mathematical modeling, expensive transformers
[30]	Numerical	Insertion Loss	Flexible	Passive	Narrow	Complex control system, nonlinear control components, transformers used
[31]	Analytical	Insertion Loss	Fixed	Passive	Wide	Alleviated method, transformers used, nonlinear control components, complex control system
[32]	Analytical	Single	Fixed	Combination	Wide	Fully integrated, tuning for load (antenna) matching, nonlinear control components
[33]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Alleviated method, complex control system, fast operating speed, low development cost
[34]	Analytical	Insertion Loss	Fixed	Passive	Narrow	Transformers used, alleviated method, complex control system, nonlinear control components
[35]	Analytical	Insertion Loss	Flexible	Combination	Narrow	Fully integrated, complex control system, expensive transformers, nonlinear control components
[36]	Analytical	Insertion Loss	Flexible	Combination	Wide	Transformers used, fully integrated, nonlinear control components, complex mathematical modeling
This work	Numerical	Insertion Loss	Flexible	Combination	Wide	Automated tuning, no need of complex mathematical modeling, linear control components, digital circuitry, simple analogue components, reliable convergence, reduction in insertion-loss, autonomous control of adaptive antenna matching networks, optimum power transfer, fully integrated

Combination: Passive and Active

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Dr. Alibakhshikenari was winner of an annual research grant started on 15/11/2019 and to be finalized in 15/11/2020, which has been funded by the Electronic Engineering Department of the University of Rome "Tor Vergata", Italy, where he is now working as a postdoctoral research fellow.

In 2018 for 8 months he was working with the Antenna System Division, Electrical Engineering Department of the Chalmers University of Technology, Gothenburg, Sweden as a Ph.D. visiting researcher. His training during the Ph.D. included a research stage in the Swedish company Gap Waves AB that is developing components in a technology.

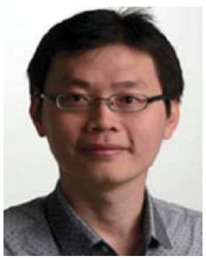
He was two recipients of the 47th and 48th European Microwave Conference (EuMC) Young Engineer Prize in 2017 (Nuremberg, Germany) and 2018 (Madrid, Spain), where he had presented his papers. He presented an invited lecture entitled "Metamaterial Applications to Antenna Systems" at the Department of Information and Telecommunication Engineering, Incheon National University, Incheon, South Korea, which was in conjunction with the 8th Asia-Pacific Conference on Antennas and Propagation (APCAP 2019), where he was chair of the "Metamaterial" session as well. Dr. Mohammad Alibakhshikenari is serving as a guest editor of a special issue entitled "Millimeter-wave and Terahertz Applications of Metamaterials" in the Applied Sciences. In April 2020 his paper entitled "High-Gain Metasurface in Polyimide On-Chip Antenna Based on CRLH-TL for Sub Terahertz Integrated Circuits" published in Scientific Reports was awarded as best month paper at the University of Bradford, UK. During his Ph.D. he was winner of 13 grants for participating in the European Doctoral Schools on Antennas and Metamaterials organized by several European Universities.

Dr. Mohammad Alibakhshikenari acts as a referee in several high reputed journals and international conferences.

Bal S. Virdee (SM’08) received the B.Sc. and MPhil degrees in Communications-Engineering from the University of Leeds-UK and his Ph.D. in Electronic-Engineering from the University of London-UK. He has worked in industry for various companies including Philips (UK) as an R&D-engineer and Filtronic-Components Ltd. as a future products developer in the area of RF/microwave communications. He has taught at several academic institutions before joining London Metropolitan University where he is a Professor of Microwave-Communications in the Faculty of Life

Sciences&Computing where he Heads the Center for Communications-Technology and is the Director of London Metropolitan-Microwaves. His research, in collaboration with industry and academia, is in the area of microwave wireless communications encompassing mobile-phones to satellite-technology. Prof. Virdee has chaired technical sessions at IEEE international conferences and published numerous research-papers. He is Executive-Member of IET's Technical and Professional Network Committee on RF/Microwave-Technology. He is a Fellow of IET and a Senior-Member of IEEE.

Mohammad Naser-Moghadasi (M'01–SM'10) was born in Saveh, Iran, in 1959. He received the BSc degree in communication Engineering in 1985 from the Leeds Metropolitan University (formerly Leeds Polytechnic), UK. Between 1985 and 1987, he worked as an RF design engineer for the Gigatech company in Newcastle Upon Tyne, UK. From 1987 to 1989, he was awarded a full scholarship by the Leeds educational authority to pursue an MPhil. Studying in CAD of microwave circuits. He received his PhD in 1993, from the University of Bradford, UK. From 1995, Dr Naser-Moghadasi joined Islamic Azad University, Science & Research Branch, Iran, where he currently is a full professor and head of computer and electrical engineering department. His main areas of interest in research are microstrip antenna, Microwave passive and active circuits, RF MEMS. He has so far published over 200 papers in different journals and conferences.



Chan Hwang See (M'14–SM'15) received the first class B.Eng. honors degree in electronic, telecommunication, and computer engineering and the Ph.D. degree in computational bioelectromagnetics from the University of Bradford, Bradford, U.K., in 2002 and 2007, respectively. He is a Senior Lecturer (Programme Leader) in Electrical and Electronic Engineering, School of Engineering, University of Bolton, Bolton, U.K. He also is a Visiting Research Fellow in the School of Engineering and Informatics, University of Bradford. Previously, he was a Senior Research Fellow in the Antennas and Applied Electromagnetics Research Group within the University of Bradford. His research interests cover wireless sensor network system design, computational electromagnetism, antennas, and acoustic sensor design. He has published more than 160 peer-reviewed journal articles and conference papers. He is a coauthor of one book and five book chapters.

Dr. See is a Chartered Engineer in the U.K., and a Member of the Institution of Engineering and Technology, U.K. He is also a Fellow of The Higher Education Academy and an Associate Editor for IEEE ACCESS.
He received two Young Scientist Awards from the International Union of Radio Science and the Asia-Pacific Radio Science Conference in 2008 and 2010, respectively. He received a certificate of excellence for his successful Knowledge Transfer Partnership with Yorkshire Water on the design and implementation of a wireless sensor system for sewerage infrastructure monitoring in 2009.

Raed A. Abd-Alhameed (M'02–SM'13) received the B.Sc. and M.Sc. degrees from Basrah University, Basrah, Iraq, in 1982 and 1985, respectively, and the Ph.D. degree from the University of Bradford, Bradford, U.K., in 1997, all in electrical engineering.

He is a Professor of electromagnetic and radio frequency engineering at the University of Bradford. He has long years' research experience in the areas of radio frequency, signal processing, propagations, antennas, and electromagnetic computational techniques, and has published more than 500 academic journal and conference papers; in addition, he is a coauthor of three books and several book chapters. He is currently the Leader of Radio Frequency, Propagation, Sensor Design, and Signal Processing; in addition to leading the Communications research group for years within the School of Engineering and Informatics, Bradford University. He is a Principal Investigator for several funded applications to EPSRCs and leader of several successful Knowledge Transfer Programmes (KTPs) such as with Arris (previously known as Pace plc), Yorkshire Water plc, Harvard Engineering plc, IETG Ltd., Seven Technologies Group, Emkay Ltd., and Two World Ltd. He has also been a Co-Investigator in several funded research projects including: H2020 MARIE Sklodowska-CURIE ACTIONS: Innovative Training Networks "Secure Network Coding for Next Generation Mobile Small Cells 5G-US," nonlinear and demodulation mechanisms in biological tissue (Department of Health, Mobile Telecommunications & Health Research Programme, and Assessment of the Potential Direct Effects of Cellular Phones on the Nervous System (EU: collaboration with six other major research organizations across Europe). He received the Business Innovation Award for his successful KTP with Pace and Datong companies on the design and implementation of MIMO sensor systems and antenna array design for service localizations. He is the Chair of several successful workshops on Energy Efficient and Reconfigurable Transceivers: Approach Towards Energy Conservation and CO2 Reduction that addresses the biggest challenges for future wireless systems. He was also appointed as a Guest Editor for IET Science, Measurements and Technology in 2009 and 2012. He has also been a Research Visitor at Glyndwr University, Wrexham, U.K., since September 2009, covering the wireless and communications research areas. His research interests include computational methods and optimizations, wireless and mobile communications, sensor design, EMC, beam steering antennas, energy-efficient PAs, and RF predistorter design applications.

Dr. Abd-Alhameed is the Fellow of the Institution of Engineering and Technology, U.K., a Fellow of the Higher Education Academy, and a Chartered Engineer in the U.K.

Francisco Falcone (M'05, SM'09) received the degree in telecommunication engineering and the Ph.D. degree in communication engineering from the Universidad Pública de Navarra (UPNA), Spain, in 1999 and 2005, respectively. From February 1999 to April 2000, he was the Microwave Commissioning Engineer at Siemens-Italtel, deploying microwave access systems. From May 2000 to December 2008, he was a Radio Access Engineer at Telefónica Móviles, performing radio network planning and optimization tasks in mobile network deployment. In January 2009, as a co-founding member, he has been the Director of Tafco Metawireless, a spin-off company from UPNA, until May 2009. In parallel, he is an Assistant Lecturer with the Electrical and Electronic Engineering Department, UPNA, from February 2003 to May 2009. In June 2009, he becomes an Associate Professor with the EE Department, being the Department Head, from January 2012 to July 2018. From January 2018 to May 2018, he was a Visiting Professor with the Kuwait College of Science and Technology, Kuwait. He is also affiliated with the Institute for Smart Cities (ISC), UPNA, which hosts around 140 researchers. He is currently acting as the Head of the ICT Section. His research interests are related to computational electromagnetics applied to the analysis of complex electromagnetic scenarios, with a focus on the analysis, design, and implementation of heterogeneous wireless networks to enable context-aware environments. He has over 500 contributions in indexed international journals, book chapters, and conference contributions. He has been awarded the CST 2003 and CST 2005 Best Paper Award, the Ph.D. Award from the Colegio Oficial de Ingenieros de Telecomunicación (COIT), in 2006, the Doctoral Award UPNA, 2010, 1st Juan Gomez Peñalver Research Award from the Royal Academy of Engineering of Spain, in 2010, the XII Talgo Innovation Award 2012, the IEEE 2014 Best Paper Award, 2014, the ECSA-3 Best Paper Award, 2016, and the ECSA-4 Best Paper Award, 2017.

Isabelle Huynen (M'96–SM'06) received the Ph.D. degree in applied sciences from the Université catholique de Louvain (UCLouvain), Louvain-laNeuve, Belgium, in 1994. Since 1999, she has been with FRS-FRNS, Bruxelles, Belgium. She is currently the Research Director and a part-time Professor with UCLouvain. Her current research interests cover nanotechnology, nanodevices and nanomaterials for microwave and millimeter wave applications, including metamaterials, antennas, and absorbers.

Tayeb A. Denidni (Fellow, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering from Laval University, QC, Canada, in 1990 and 1994, respectively. He was a Professor with the Engineering Department, Université du Quebec in Rimouski, Rimouski, QC, Canada, from 1994 to 2000, where he founded the Telecommunications Laboratory. Since 2000, he has been with the Institut National de la Recherche Scientifique (INRS), Université du Quebec, Montreal, QC, Canada. He founded the RF Laboratory with INRS-EM, Montreal. He has extensive experience in antenna design and is leading a large research group consisting of three research scientists, eight Ph.D. students, and two M.Sc. students. His current research interests include reconfigurable antennas using EBG and FSS structures, dielectric resonator antennas, metamaterial antennas, adaptive arrays, switched multibeam antenna arrays, ultrawideband antennas, microwave, and development for wireless communications systems. Dr. Denidni has served as an Associate Editor for the IEEE ANTENNAS WIRELESS PROPAGATION LETTERS, from 2005 to 2007, and the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, from 2008 to 2010. Since 2015, he has been serving as an Associate Editor for the IET Electronics Letters.

Ernesto Limiti (S'87–M'92–SM'17) is a full professor of Electronics in the Engineering Faculty of the University of Roma Tor Vergata since 2002, after being research and teaching assistant (since 1991) and associate professor (since 1998) in the same University. Ernesto Limiti represents University of Roma Tor Vergata in the governing body of the MECSA (Microwave Engineering Center for Space Applications), an inter-universitary center among several Italian Universities. He has been elected to represent the Industrial Engineering sector in the Academic Senate of the University for the period 2007-2010 and 2010-2013. Ernesto Limiti is actually the president of the Consortium "Advanced research and Engineering for Space", ARES, formed between the University and two companies. Further, he is actually the president of the Laurea and Laurea Magistrale degrees in Electronic Engineering of the University of Roma Tor Vergata. The research activity of Ernesto Limiti is focused on three main lines, all of them belonging to the microwave and millimetre-wave electronics research area. The first one is related to characterisation and modelling for active and passive microwave and millimetre-wave devices. Regarding active devices, the research line is oriented to the small-signal, noise and large signal modelling. Regarding passive devices, equivalent-circuit models have been developed for interacting discontinuities in microstrip, for typical MMIC passive components (MIM capacitors) and to waveguide/coplanar waveguide transitions analysis and design. For active devices, new methodologies have been developed for the noise characterisation and the subsequent modelling, and equivalent-circuit modelling strategies have been implemented both for small and large-signal operating regimes for GaAs, GaN, SiC, Si, InP MESFET/HEMT devices. The second line is related to design methodologies and characterisation methods for low noise circuits. The main focus is on cryogenic amplifiers and devices. Collaborations are currently ongoing with the major radioastronomy institutes all around Europe within the frame of FP6 and FP7 programmes (RadioNet). Finally, the third line is in the analysis methods for nonlinear microwave circuits. In this line, novel analysis methods (Spectral Balance) are developed, together with the stability analysis of the solutions making use of traditional (harmonic balance) approaches. The above research lines have produced more than 250 publications on refereed international journals and presentations within international conferences. Ernesto Limiti acts as a referee of international journals of the microwave and millimetre wave electronics sector and is in the steering committee of international conferences and workshops. He is actively involved in research activities with many research groups, both European and Italian, and he is in tight collaborations with high-tech italian (Selex - SI, Thales Alenia Space, Rheinmetall, Elettronica S.p.A., Space Engineering …) and foreign (OMMIC, Siemens, UMS, …) companies. He contributed, as a researcher and/or as unit responsible, to several National (PRIN MIUR, Madess CNR, Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, RadioNet FP6 and FP7 …) projects.

Regarding teaching activities, Ernesto Limiti teaches, over his istitutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, "Elettronica per lo Spazio" within the Master Course in Sistemi Avanzati di Comunicazione e Navigazione Satellitare. He is a member of the committee of the PhD program in Telecommunications and Microelectronics at the University of Roma Tor Vergata, tutoring an average of four PhD candidates per year.

Resubmission of Manuscript ID TMTT-2019-10-1185

While the topic of manuscript is of interest to TMTT, the paper does not put the submitted work in context with recent work and clearly articulate the new contribution. In the references, there is only 1 TMTT reference after 2008, and that was in 2010 - 9 years ago. The manuscript should have recent references, in particular in this topic area as there are numerous works on this subject. In addition, the manuscript does not clearly state what is current state of the art and what specifically is the new contribution. The paper must contain clear information about what is current state of the art and what is the new specific contribution.

You may submit a new manuscript, however please address all of the concerns above. In particular, I encourage you to submit 3 related and recent (past 3 years) works.

Authors Reply: Dear Dr. David Ricketts, Thank you for your valuable time and providing us your constructive feedback. Regarding your comments, we have provided a comparison section before concluding the paper. We have listed several recent publications in Table 1 to comparing them with our proposed work. We wish it could be helpful to better evaluate our work and its achievements.

We did a similarity check and unfortunately it seems that our manuscript text has been saved in the Turnitin database (similarity checker) as "London Metropolitan University", which is the affiliation of Prof. Bal S. Virdee. Please note, the paper or some part of that is not published anywhere. They told us they have deleted it. We just wanted to inform you.

Best Regards,

Mohammad Alibakhshikenari, and on-behalf of co-authors