TeKCEM

Presentation of the MIMOmatch-G patent portfolio

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SUMMARY OF THE MIMOmatch-G PATENT PORTFOLIO

Sector: wireless communication
Technical area: automatic antenna tuning

Table I. Patent families of the MIMOmatch-G patent portfolio	
Title of the patent family	Family
Method for automatic adjustment of a tunable matching circuit, and automatic tuning system using this method	P65
Method of automatic adjustment of a tunable matching circuit, and automatic tuning system using this method	P66
Method for automatic adjustment of a tunable passive antenna and a tuning unit, and apparatus for radio communication using this method	P73
Method for automatically adjusting a tunable passive antenna and a tuning unit, and apparatus for radio communication using this method	P74

Status: each patent family includes a granted patent of the U.S.A. Link to the patents

Short description: The MIMOmatch-G portfolio consists of the inventions P65, P66, P73 and P74 of Tekcem, which belong to the space "adaptive antenna tuning for a wireless device using one or more antennas". The inventions of this portfolio have the following characteristics:
- they use an antenna tuner and are suitable for user equipments (UEs) of wireless networks;
- they use an open-loop control step, followed by an extremum-seeking control step providing an accurate maximization of output power and efficiency during emission, over a broad frequency range;
- they adaptively compensate the effects of the electromagnetic characteristics of the surroundings (including the user interaction), to deliver an optimal automatic tuning, even when antenna tuner losses are significant;
- they explicitly cover uplink and downlink antenna selection techniques.

Disclaimer: information contained herein is believed to be reliable, but no warranty is given as to its accuracy or completeness.

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1. Listing of the MIMOmatch-G portfolio

Table II. Items of the MIMOmatch-G patent portfolio						
Item ID	Jurisdiction	Appl. no.	Filing date	Patent or PCT publ. no.	Issue date	Family
P65-A	France	16/70337	22 Jun. 2016	pending	pending	P65
P65-B	PCT	PCT/IB2017/053244	01 Jun. 2017	WO 2017/221089	N/A	
P65-C	U.S.A.	15/789,568	20 Oct. 2017	9,935,607	03 Apr. 2018	
P66-A	France	16/70357	30 Jun. 2016	pending	pending	P66
P66-B	PCT	PCT/IB2017/053267	02 Jun. 2017	WO 2018/002745	N/A	
P66-C	U.S.A.	15/795,822	27 Oct. 2017	9,966,924	08 May 2018	
P73-A	France	17/70536	24 May 2017	FR1770536	14 Jun. 2019	P73
P73-B	PCT	PCT/IB2017/056470	18 Oct. 2017	WO 2018/215820	N/A	
P73-C	U.S.A.	15/801,708	02 Nov. 2017	10,044,380	7 Aug. 2018	
P74-A	France	17/70537	25 May 2017	FR1770537	14 Jun. 2019	P74
P74-B	PCT	PCT/IB2017/056501	19 Oct. 2017	WO 2018/215821	N/A	
P74-C	U.S.A.	15/814,689	16 Nov. 2017	9,991,911	5 June 2018	

At the date of this document, Tekcem is the sole owner of and has good and marketable title to the items listed in Table II, which are free and clear of all liens, mortgages, security interests or other encumbrances, and restrictions on transfer. At the date of this document, no rights or licenses have been granted under the items listed in Table II.

2. Notes on terminology

Antenna interaction. Antenna interaction between the antennas of a multiport antenna array results in a significantly non-diagonal impedance matrix. It is caused by a narrow spacing between the antennas, and is more pronounced in the lower frequency bands. Antenna interaction may produce a mismatch loss and noise in the downlink, a mismatch loss and cross modulation in the uplink, and antenna correlation.

Antenna tuner (AT). Traditional antenna tuners have a single input port and a single output port. The inventions P65, P66, P73 and P74 use a single-input-port and single-output-port antenna tuner, referred to as “single-input-port and single-output-port tunable matching circuit” in P65 and P66, and as “single-input-port and single-output-port tuning unit” in P73 and P74. Several other inventions of Tekcem use a multiple-input-port and multiple-output-port antenna tuner.

Aperture tuning. Aperture tuning means adjusting one or more tunable passive antennas.

Closed-loop. “closed-loop control”, also referred to as “feedback control”, means control in which the control action is made to depend on a measurement of the controlled variable (see “IEC multilingual dictionary of electricity” edited by the *Bureau Central de la Commission Electrotechnique Internationale*).

Effects of the electromagnetic characteristics of the surroundings (EECS). The effects, on a wireless link, of the interaction between the one or more antennas of a user equipment (UE) and the medium surrounding these antennas. These effects comprise:

- ◆ a variation in the impedance of the antenna, or in the impedance matrix of the antennas;
- ◆ a variation in the radiation efficiency;
- ◆ a variation in the directivity of the system formed by the UE and the user.

For instance, the electromagnetic interaction between an antenna and a user holding the UE, often referred to as “user interaction” and illustrated below, can severely degrade the radio link.

Extremum-seeking control. Extremum-seeking control is a family of nonlinear control methods whose purpose is to autonomously find either a maximum or a minimum of a performance variable, the performance variable being a real function of one or more outputs of a controlled system, by controlling one or more inputs of the controlled system. The inventions P65, P66, P73 and P74 use extremum-seeking control. Each includes a detailed (and broad) definition of extremum-seeking control.

Impedance tuning. Impedance tuning means adjusting one or more antenna tuners.

Open-loop. In the literature on antenna tuners, “open-loop” often erroneously refers to a control scheme without measurement of an electrical variable, so that the antenna tuner is typically adjusted only as a function of the operating frequency. In this document and in line with standard terminology, “open-loop control” means control which does not utilize a measurement of the controlled variable (see “IEC multilingual dictionary of electricity” edited by the *Bureau Central de la Commission Electrotechnique Internationale*).

Tunable passive antenna (TPA). The inventions P73 and P74 use one or more tunable passive antennas. Each patent application includes a detailed definition of a tunable passive antenna.

User interaction. See Effects of the electromagnetic characteristics of the surroundings (EECS), above.

3. Context and state of the art

In current premium tier mobile phone designs, automatic antenna tuning, which adjusts a tunable passive antenna (TPA) and/or an antenna tuner (AT) to improve performance, has become increasingly prominent as a method to support the growing range of LTE frequencies, and to mitigate possible effects of the electromagnetic characteristics of the surroundings (EECS). For instance, the electromagnetic interaction between an antenna and a user holding the mobile phone, often referred to as *user interaction*, can severely degrade the radio link, unless antenna tuning is implemented.

Antenna tuning is taken into account in MIPI alliance specifications, and many manufacturers provide components for antenna tuning or implement them in LTE user equipments (UEs). For instance, one of the key aspects of the latest high-performance modems of Qualcomm is their antenna tuning capability, which may use “Qualcomm® TruSignal™ antenna boost technology” and “Qualcomm® RF360 dynamic antenna matching tuner”. For instance, an IHS Markit teardown of a Galaxy S8+ found that the smartphone uses both impedance tuning and aperture tuning solutions from Qualcomm, the QAT3550 and the QAT3514.

Antenna tuning can be used to: reduce the size of the antennas, allow to use them on more frequencies, and improve the characteristics of the radio link. Thus, it increases the overall power efficiency, signal consistency, and achievable data speed. For consumers, automatic antenna tuning can provide a better data and voice experience indoors and outdoors, and longer battery life. For original equipment manufacturers (OEMs), automatic antenna tuning may help reduce product size (form factor), and time-to-certification, by addressing the risk of redesign iterations caused by insufficient antenna performance. It is recognized that fast and accurate antenna tuning will play a more important role in UEs for 5G.

Many methods are available for automatically tuning a single-input-port and single-output-port AT. The article shown in Annex B defines several types of antenna tuner control scheme. The types which can directly maximize the average power radiated by the antenna during emission (or equivalently, maximize the average power delivered by the antenna port of the AT during emission) are the type 0, type 3 and type 4 control schemes (see Table I of the article, in page A-6 below). Type 0 and type 3 use open-loop control and are model-based. Type 0 is inherently inaccurate. Type 3 is more accurate and can effectively compensate the effects of the electromagnetic characteristics of the surroundings (EECS). However, prior art automatic antenna tuning systems using a type 3 control scheme for the AT have the following limitations:

- they often only provide a medium accuracy over the relevant temperature range;
- they require complicated vector measurements at the antenna port;
- their tuning frequency-range is not broad, in contrast to the requirements of LTE and 5G New Radio; and
- they ignore all multi-antenna techniques used in LTE and 5G New Radio.

4. Technical presentation of the inventions

Antenna selection is a multi-antenna technique used in LTE and 5G New Radio (it was the only uplink multi-antenna technique available for the UE of LTE in 3GPP release 8). All patent families of the MIMOmatch-G patent portfolio explicitly cover uplink and downlink antenna selection techniques (see 20th embodiment and Fig. 19 of P65-B; 14th embodiment, 16th embodiment, Fig. 17 and Fig. 19 of P66-B; 17th embodiment and Fig. 23 of P73-B; and 19th embodiment and Fig. 24 of P74-B). This is why, in what follows, we consider a wireless device comprising one or more antennas, or one or more tunable passive antennas (TPAs).

All patent families of the MIMOmatch-G patent portfolio implement an automatic adjustment of a single-input-port and single-output-port antenna tuner (AT), using the new type 4 control scheme defined in the article shown in Annex B. This control scheme combines: a step based on open-loop control, for speed; with a step implementing an extremum-seeking control algorithm (see § 2 above), for accurately maximizing the average power radiated by the antenna during emission, or equivalently the average power delivered by the antenna port of the AT during emission, or equivalently the insertion gain of the AT during emission.

The inventions P65 and P73 use a type 4 subtype *a* control scheme, in which the step based on open-loop control uses one of the type 0 control schemes. The inventions P66 and P74 use a type 4 subtype *b* control scheme, in which the step based on open-loop control uses a type 3 control scheme. This approach is more expensive, but much faster.

In the patent families P73 and P74, a preliminary automatic adjustment of the one or more TPAs used for radio communication provides a coarse tuning, and is followed by an automatic adjustment of the AT providing a fine tuning. In this way, an accurate adjustment of the AT can be obtained over a much broader frequency range than with one or more non-tunable antennas, and faster. In the case of P74, the automatic adjustment of the one or more TPAs has another advantage: it reduces the size of the part of the complex plane in which reasonably accurate impedance measurements are needed to perform the step based on open-loop control.

The patent references cited during the prosecution of P65-C, P66-C, P73-C and P74-C by the USPTO are summarized in Annex A below. Some characteristics of the inventions are summarized in Table III, where a number in brackets, for instance (2), refers to one of the notes following the table, where the column “AT control scheme” refers to the control scheme used to automatically adjust the AT, and where the column “TPA control scheme” refers to the control scheme used to automatically adjust the one or more TPAs.

Table III. Characteristics of the inventions of the MIMOmatch-G patent portfolio

Family	Antennas	Measurements	AT control scheme	TPA control scheme
P65	one or more	scalar at output port	type 4 subtype *a*	none
P66	one or more	vector at output port	type 4 subtype *b*	none
P73	one or more	scalar at output port	type 4 subtype *a*	open-loop or closed-loop (1)
P74	one or more	vector at output port	type 4 subtype *b*	open-loop or closed-loop (2)

Note 1: for instance, in the PCT application of P73, see page 11 lines 9 to 15; page 26 lines 7 to 14; page 32 lines 8 to 12; page 42 lines 6 to 11; and page 62 lines 17 to 24.

Note 2: for instance, in the PCT application of P74, see page 11 lines 6 to 12; page 28 lines 4 to 11; page 34 lines 11 to 21; and page 47 lines 16 to 21.

This presentation shows that the inventions of the MIMOmatch-G porfolio can be used to simultaneously:
■ obtain a sufficiently fast automatically tuning of a single-input-port and single-output-port AT, by utilizing a step based on open-loop control;
■ obtain an accurate maximization of output power and efficiency during emission, by utilizing a step based on extremum-seeking control;
■ operate over a broad frequency range, as allowed by the automatic adjustment of TPAs and of the AT;
■ adaptively compensate the effects of the electromagnetic characteristics of the surroundings (including the user interaction), to deliver an optimal automatic tuning, even when antenna tuner losses are significant;
■ be used in combination with uplink and downlink antenna selection techniques.

5. Frequently asked questions

Question 1. Is there any standard-essential patent in the MIMOmatch-G portfolio ?

Answer 1. No. Note that Tekcem is not a member of any standard-setting organization, and that no patent of the MIMOmatch-G portfolio is subject to FRAND conditions.

Question 2. What is the MIMOmatch-G portfolio useful for ?

Answer 2. The MIMOmatch-G portfolio is important for manufacturers of UEs, (for instance Samsung, Apple, Huawei, etc), and for the manufacturers of baseband processors (for instance Samsung, Qualcomm, MediaTek, Intel, etc), because it discloses several advantageous antenna tuning control schemes.

Question 3. Is any third party currently using an invention of the MIMOmatch-G portfolio ?

Answer 3. We do not know, but it is possible. Manufacturers do not publicly disclose the antenna tuning control schemes used in their products. Thus, detecting infringement requires some investigation. Note that, in a global first-to-file patent system, relying on secrecy is very dangerous for manufacturers, because secrets and confidential disclosures are not part of prior art.

The lack of evidence of use is not the best configuration for an NPE seeking quick profit. This portfolio is meant to be acquired by a manufacturer who is looking for the best solution for his products.

Question 4. Is an infringement of the MIMOmatch-G portfolio easy to detect ?

Answer 4. Yes, for a manufacturer of UEs, this is easy.

Detecting an infringement is easy because you do not need to know the exact algorithms that are being used. To determine the method which is implemented, you can look at the hardware and find out: (a) if an AT and/or one or more TPAs are used; (b) how the tuning control signals received by the AT and/or the one or more TPAs behave when the operating frequency changes; (c) how the tuning control signals received by the AT and/or the one or more TPAs behave when an object is moved in the vicinity of the antennas; and (d) if the hardware makes measurements before the AT or after the AT. Detecting an infringement only requires an inspection of the UE circuits, and simple measurements across discrete devices. There is no need to look at the silicon inside chips, or to know the signal processing code. All this is simple for a manufacturing company.

Question 5. Is there a relationship between the prior art patents US 7,535,312, US 7,714,676, and US 8,299,867 on the one part, and the inventions of the MIMOmatch-G portfolio on the other part?

Answer 5. These prior art patents are listed in the “Reference Cited” section of P65-C, P66-C, P73-C and P74-C (see Annex A). They have consequently been considered by the examiner of the USPTO, who found that they do not anticipate our inventions.

The patents US 7,535,312, US 7,714,676, and US 8,299,867 of W.E. McKinzie, III, assigned to Paratek Microwave, Inc. or to Research In Motion RF, Inc., and other disclosures of the same inventor, have different claims but are otherwise almost identical. They disclose an automatic tuning system using an algorithm, the description of the algorithm being succinct since the specifications of the patents only indicate that:

> "The purpose of the control system shown in FIG. 1 is to monitor the output RF voltage magnitude and to use this information as an input to an algorithm that adjusts the tuning voltages provided to the tunable reactive elements in the RF matching network 110. The algorithm adjusts the reactances to maximize the RF output 115 voltage. Various options exist for control algorithms. In general, the algorithm may be a scalar multi-dimensional maximization algorithm where the independent variables are the tuning voltages for the reactive elements."

and

> "The controller may use external signals such as knowledge of frequency, Tx or Rx mode, or other available signals in the operation of its control algorithm."

The wording "scalar multi-dimensional maximization algorithm" used in these prior art patents does not appear anywhere else in the literature, and this wording is self-contradictory since "scalar" is not compatible with "multi-dimensional".

The term "maximization algorithm" used in these prior art patents usually refers to a computational technique to determine a maximum of a function, instead of a control technique. As explained in the PCT application of P65 in page 20 lines 7 to 23, in the PCT application of P66 in page 21 lines 8 to 24, in the PCT application of P73 from page 30 line 29 to page 31 line 6, and in the PCT application of P74 in page 32 lines 22 to 38, the specialist sees fundamental differences between a minimization algorithm or a maximization algorithm, on the one part, and the extremum-seeking control algorithm used in the inventions of the MIMOmatch-G portfolio, on the other part:

■ a minimization algorithm or a maximization algorithm autonomously finds an extremum of a known function (typically stored in a computer), without real-time constraint;

■ in contrast, the extremum-seeking control algorithm autonomously finds, in real-time, a maximum or a minimum of a performance variable, without knowing an exact model of the controlled system (non-model-based optimization approach), the controlled system being dynamic (it varies over time), and the performance variable containing noise from the measurements and from the output(s) of the controlled system.

Additionally, these prior art patents provide no indication on how a "scalar multi-dimensional maximization algorithm" could use "external signals" or "other available signals".

Thus, no meaningful indication is given about the "maximization algorithm" referred to as in said prior art patents, except that it is assumed to perform a result to be achieved: maximizing the rf output voltage. Moreover, we observe that this result to be achieved is not appropriate, if the rf output voltage is amplitude modulated. This may be understood based on explanations relating to the MIMOmatch-G portfolio, provided in Section VII of the article shown in Annex B, or in the 9th embodiment of the PCT application of P65, or the 8th embodiment of the PCT application of P66, or in the 3rd embodiment of the PCT application of P73, or in the 3rd embodiment of the PCT application of P74.

The nature of the algorithm being obscure, we do not believe that the inventions presented in said prior art patents are disclosed in a manner sufficiently clear and complete for them to be carried out by a person skilled in the art. It is therefore difficult to compare said prior art patents to the MIMOmatch-G portfolio.

6. Presentation of Tekcem

6.1 Business model of Tekcem

The main business of Tekcem has three steps: first, Tekcem purchases R&D work of the Excem group, in the form of reports and software, the report contractually including the description of inventions; second, Tekcem files and prosecutes patent applications for said inventions; third, Tekcem sells intellectual property rights for the inventions (patent applications and patents), and, separately, the know-how and software.

6.2 Information about inventions previously sold by Tekcem

Tekcem has sold the following 13 inventions of the Excem group in the area of radio communication, under the trademark MIMOmatch:

[P62] French patent appl. 15/01780 of 26 August 2015, international appl. PCT/IB2015/057161 of 17 September 2015 (WO 2017/033048), and US patent No. 9,966,930. Method for automatically adjusting a tuning unit, and automatic tuning system using this method. Sold to Samsung Electronics, Co, Ltd in 2016, as a part of patent porfolio MIMOmatch-D.

[P61] French patent appl. 15/01290 of 22 June 2015, international appl. PCT/IB2015/057131 of 16 September 2015 (WO 2016/207705), and US patent No. 10,116,057. Method and apparatus for automatic tuning of an impedance matrix, and radio transmitter using this apparatus. Sold to Samsung Electronics, Co, Ltd in 2016, as a part of patent porfolio MIMOmatch-D.

[P60] French patent appl. 14/01221 of 28 May 2014, international appl. PCT/IB2015/052974 of 23 April 2015 (WO 2015/181653), and US patent No. 10,224,901. Radio communication using a plurality of selected antennas. Sold to Samsung Electronics, Co, Ltd in 2015, as a part of patent porfolio MIMOmatch-C.

[P59] French patent appl. 14/00666 of 20 March 2014, international appl. PCT/IB2015/051644 of 6 March 2015 (WO 2015/140660), and US patent No. 9,680,510. Radio communication using tunable antennas and an antenna tuning apparatus. Sold to Samsung Electronics, Co, Ltd in 2015, as a part of patent porfolio MIMOmatch-C.

[P58] French patent appl. 14/00606 of 13 March 2014, international appl. PCT/IB2015/051548 of 3 March 2015 (WO 2015/136409), and US patent No. 9,654,162. Radio communication using multiple antennas and localization variables. Sold to Samsung Electronics, Co, Ltd in 2015, as a part of patent porfolio MIMOmatch-C.

[P57] French patent appl. 13/00878 of 15 April 2013, international appl. PCT/IB2014/058933 of 12 February 2014 (WO 2014/170766), and US patent No. 9,077,317. Method and apparatus for automatically tuning an impedance matrix, and radio transmitter using this apparatus. Sold to Samsung Electronics, Co, Ltd in 2015, as a part of patent porfolio MIMOmatch-B.

[P56] French patent appl. 13/00665 of 21 March 2013, international appl. PCT/IB2013/060481 of 28 November 2013 (WO 2014/147458), and US patent No. 9,294,174. Method and device for radio reception using a plurality of antennas and a multiple-input-port and multiple-output-port amplifier. Sold to Samsung Electronics, Co, Ltd in 2015, as a part of patent porfolio MIMOmatch-B.

[P55] French patent appl. 12/02564 of 27 September 2012, international appl. PCT/IB2013/058574 of 16 September 2013 (WO 2014/049486), and US patent No. 9,337,534. Method and device for radio reception using an antenna tuning apparatus and a plurality of antennas. Sold to Samsung Electronics, Co, Ltd in 2015, as a part of patent porfolio MIMOmatch-B.

[P54] French patent appl. 12/02542 of 25 September 2012, international appl. PCT/IB2013/058423 of 10 September 2013 (WO 2014/049475), and US patents No. 9,621,132 and No. 10,187,033. Antenna tuning apparatus for a multiport antenna array. Sold to Samsung Electronics, Co, Ltd in 2015, as a part of patent porfolio MIMOmatch-B.

[P41] French patent appl. 08/03982 of 11 July 2008, international appl. PCT/IB2009/051358 of 31 March 2009 (WO 2010/004445), and US patent No. 7,952,429. Multiple-input and multiple-output amplifier having pseudo-differential inputs. Sold to Apple, Inc. in 2012, as a part of patent porfolio MIMOmatch-A.

[P34] French patent appl. 06/06502 of 18 July 2006, international appl. PCT/IB2007/001589 of 5 June 2007 (WO 2008/010035), and US patent No. 7,983,645. Method and device for radio reception using a plurarity of antennas. Sold to Apple, Inc. in 2012, as a part of patent porfolio MIMOmatch-A.

[P33] French patent appl. 06/05633 of 23 June 2006, international appl. PCT/IB2007/001344 of 26 April 2007 (WO 2008/001168), and US patent No. 7,940,119. Multiple-input and multiple-output amplifier using mutual induction in the feedback network. Sold to Apple, Inc. in 2012, as a part of patent porfolio MIMOmatch-A.

[P30] French patent appl. 06/00388 of 17 January 2006, international appl. PCT/IB2006/003950 of 19 December 2006 (WO 2007/083191), and US patent No. 7,642,849. Multiple-input and multiple-output amplifier. Sold to Apple, Inc. in 2012, as a part of patent porfolio MIMOmatch-A.

Thus, Tekcem sold, in the area of radio communication:

- 9 inventions (P54 to P62) to Samsung Electronics, Co, Ltd, in 2015 and 2016; and
- 4 inventions (P30, P33, P34 and P41), to Apple, Inc., in 2012.

Tekcem also sold 16 inventions on signal integrity and integrated circuit interfaces, including 2 inventions sold to Apple, Inc. in 2012.

7. The inventors

The inventors of the MIMOmatch-G portfolio are Evelyne Clavelier and Frédéric Broyde.

Link to an on-line list of their patent applications

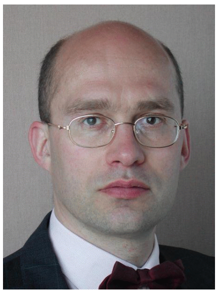
Link to an on-line list of their published articles

Evelyne Clavelier was born in France in 1961. She received the M.S. degree in physics engineering from the Ecole Nationale Supérieure d'Ingénieurs Electriciens de Grenoble (ENSIEG). She is a senior member of the IEEE.

She is co-founder of the Excem corporation, based in Maule, France. She is CEO of Excem. She is also manager of Eurexcem (a subsidiary of Excem) and President of Tekcem, a company selling or licensing intellectual property rights. She is also an active engineer and researcher. Her current research area is radio communications. She has also done research work in the areas of electromagnetic compatibility (EMC) and signal integrity. She has taken part in many electronic design and software design projects of Excem.

Prior to starting Excem in 1988, she worked for Schneider Electrics (in Grenoble, France), STMicroelectronics (in Grenoble, France), and Signetics (in Mountain View, USA).

Ms. Clavelier is the author or a co-author of about 80 technical papers. She is co-inventor of about 80 patent families. She is a licensed radio amateur (F1PHQ).



Frédéric Broydé was born in France in 1960. He received the M.S. degree in physics engineering from the Ecole Nationale Supérieure d'Ingénieurs Electriciens de Grenoble (ENSIEG) and the Ph.D. in microwaves and microtechnologies from the Université des Sciences et Technologies de Lille (USTL). He is a senior member of the IEEE.

He co-founded the Excem corporation in May 1988, a company providing engineering and research and development services. He is president and CTO of Excem. Most of his activity is allocated to engineering and research in electronics. Currently, his most active research areas is wireless transmission systems, with an emphasis on antenna tuning.

Dr. Broydé is author or co-author of about 100 technical papers, and inventor or co-inventor of about 80 patent families, for which 48 US patents have been granted. He is a licensed radio amateur (F5OYE).

Annexes

ANNEX A

Patent citations listed in P65-C, P66-C, P73-C and P74-C

Table 1: cited U.S. applications

	cited in:					
Pub. No.	P65	P66	P73	P74	Status	Applicant
2003/0174100	yes	yes	yes	yes	granted as 6,806,836	
2010/0073103	yes	yes	yes	yes	granted as 8,072,285	
2010/0182216	yes	yes	yes	yes	granted as 9,054,772	
2010/0248649				yes	granted as 8,472,904	
2016/0043526				yes	granted as 9,972,962	University of Washington
2017/0176954				yes	granted as 10,209,684	Johnson Control Technology
2018/0041184		yes			granted as 9,935,607	Tekcem [P65]

Table 2: cited U.S. patents

	cited in:					
Pat. No.	P65	P66	P73	P74	Inventor	Assigned to
2,523,791	yes	yes			Vahle et al.	General Electric Company (US)
2,745,067	yes	yes			True et al.	
3,443,231	yes	yes			Roza	Gulf General Atomic Inc. (US)
4,234,960				yes	Spilsbury et al.	Ashton James Spilsbury
4,356,458	yes	yes	yes	yes	Armitage	Harry H. LeVeen (US)
4,493,112	yes	yes			Bruene	Rockwell Int. Corp. (US)
5,525,847	yes	yes	yes	yes	Roberts et al.	Antenna Research Associates (US)
5,564,086	yes	yes			Cygan et al.	Motorola (US)
6,414,562	yes	yes			Bouisse et al.	Motorola (US)
6,806,836	appl*	appl*	appl*	appl*	Ogawa et al.	Matsushita Electric Ind. Co. (JP)
7,463,870			yes	yes	Peussens et al.	Thomson Licensing (FR)
7,535,312	yes	yes	yes	yes	McKinzie, III	Paratek Microwave (US)
7,714,676	yes	yes	yes	yes	McKinzie, III	Paratek Microwave (US)

8,072,285	appl*	appl*	appl*	appl*	Spears	Paratek Microwave (US)
8,190,109	yes	yes			Ali et al.	Research In Motion Limited (CA)
8,299,867	yes	yes	yes	yes	McKinzie, III	Research In Motion RF (US)
8,472,904				appl*	White	The Charles Stark Draper Lab. (US)
9,054,772	appl*	appl*	appl*	appl*	Schmidhammer	Qualcomm (US)
9,628,135			yes	yes	Broyde et al. [P64]	Tekcem (FR)
9,680,510			yes	yes	Broyde et al. [P59]	Samsung (KR)
9,935,607		appl*			Broyde et al. [P65]	Tekcem (FR)
9,972,962				appl*	Kutz et al.	University of Washington (US)
10,209,684				appl*	Salsbury et al.	Johnson Control Technology (US)

* "appl" means that only the US application is cited (refer to Table 1 for the corresponding US application)

Table 3: cited FR patent publications

		cited in:				
Pub. No.	Appl. No.	P65	P66	P73	P74	Applicant
3018973	FR14/00666			yes	yes	Tekcem (FR) [P59]

Table 4: cited PCT publications

	cited in:				
PCT Publication No.	P65	P66	P73	P74	Applicant
WO 2015/140660			yes	yes	Tekcem (FR) [P59]

A Typology of Antenna Tuner Control Schemes

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***Abstract* — We identify five types of antenna tuner control scheme, which are suitable for a wireless transmitter. One of them is new. Four of the five types use a single sensing unit measuring electrical variables either at the radio port or at the antenna port of the antenna tuner. Among these four types, one uses only open-loop control, whereas the others use closed-loop control, often after a preliminary open-loop step. We investigate the accuracy of the different schemes. The accuracy and other characteristics of the different schemes are discussed and compared, to help system designers to select the best control schemes for their applications.**

***Keywords* — Control system, impedance matching, antenna tuner, radio transmitter, extremum seeking.**

I. Introduction

The characteristics of an antenna may be modified by the effects of the electromagnetic characteristics of the surroundings (EECS). For a portable wireless device, a cause of EECS is the electromagnetic interaction between the antenna and a person holding the portable wireless device, often referred to as "user interaction". In current flagship mobile phone designs, automatic antenna tuning, which automatically adjusts a tunable passive antenna (TPA) and/or an antenna tuner (AT), has become increasingly prominent as a method to support the growing range of LTE or 5G frequencies, to mitigate the EECS, to reduce the size of the antennas, increase overall power efficiency and signal consistency, and obtain the highest possible data transmission rates [1] [2]. Automatic ATs are also common in land mobile, marine and tactical HF radio transceivers, as well as in radio transceivers for the amateur service [3].

This paper is about control schemes which can be used, in a radio transceiver or radio transmitter, to automatically adjust an antenna tuner. As shown in Fig. 1, the AT has a port, referred to as "antenna port", which is directly or indirectly coupled to an antenna, and another port, referred to as "radio port", for transmitting and/or receiving radio signals through the AT and the antenna. In the case of a transceiver using time-domain duplex (TDD), each port may be an input port or an output port, depending on whether emission or reception is taking place. In the case of a transceiver using frequency-domain duplex (FDD), both ports are input ports and output ports, simultaneously.

Some authors have proposed descriptions of AT control schemes which are applicable to a transmitter, and defined categories [4]-[6]. Sections II to VIII and the Appendix provide a review of existing AT control schemes, a new classification into 5 types, and a new analysis of their accuracy. Type 4 is new, and is therefore explained in detail. In Section IX, we qualitatively compare the different types. Section X provides simulations of some properties of the different schemes, for a particular antenna and a particular AT. This material should help system designers to select the most appropriate control schemes for their applications.

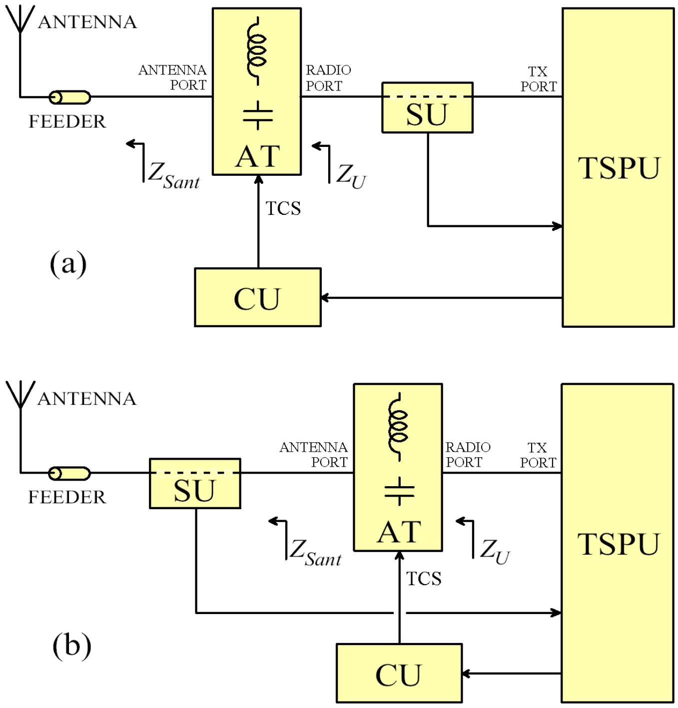

Fig. 1. Two possible configurations of a transmitter comprising an antenna, an antenna tuner (AT), a sensing unit (SU), a control unit (CU) and a transmission and signal processing unit (TSPU).

II. Definitions and Assumptions

Several control schemes, which can be used to automatically adjust an AT of a wireless transmitter, are based on one of the two configurations shown in Fig. 1. In both configurations, the transmitter comprises: an antenna; an AT; a sensing unit (SU) which senses electrical variables; a control unit (CU); and a transmission and signal processing unit (TSPU) which consists of all parts of the transmitter not shown elsewhere in Fig. 1.

The TX port of the TSPU delivers an excitation which is a bandpass signal having a carrier frequency denoted by f_C. The SU delivers, to the TSPU, one or more sensing unit output signals determined by one or more electrical variables (such as voltage, current, incident or forward voltage, etc) caused by the excitation, sensed at the radio port in the case of Fig. 1(a) or at the antenna port in the case of Fig. 1(b). The CU is an interface that delivers at least one tuning control signal (TCS) to the AT.

The AT comprises one or more adjustable impedance devices (AIDs) each having a reactance which is adjustable by electrical means. Adjusting an AT means adjusting the reactance of one or more of its AIDs. At a given time τ, a nominal reactance of an AID at f_C is determined by initial conditions of the AID at an earlier time τ_0, and by the history of at least one TCS in the time interval $[\tau_0, \tau]$. The reactance and the resistance of the AID are functions of the nominal reactance of the AID and of other variables such as temperature, humidity, aging, uncertainties, etc. The resistance of the AID is unwanted because it entails an unwanted loss.

We identify 3 AID categories, each requiring particular TCSs. They may be defined as follows:

- category 1 refers to an AID which can only provide a finite set of nominal reactance values at f_C (e.g., an AID which is a network comprising capacitors or coils or stubs, and one or more electrically controlled switches or change-over switches, such as electro-mechanical relays, or MEMS switches, or PIN diodes, or insulated-gate FETs, used to cause different capacitors or coils or stubs of the network to contribute to the reactance [1], [7]);
- category 2 refers to an AID which can provide a real interval of nominal reactance values at f_C, and such that, after a delay larger than the response time of the AID, its nominal reactance at f_C is mainly determined by the present value of at least one TCS (e.g., an AID whose reactance is determined by one or more variable capacitance diodes, or barium strontium titanate varactors [1]);
- category 3 refers to an AID which can provide a real interval of nominal reactance values at f_C, and which does not belong to category 2 (e.g., an AID such as a motorized variable capacitor, or a motorized roller inductor, in which the one or more TCSs applied to the motor cause a variation of the nominal reactance value at f_C [3]).

AIDs of categories 1 and 2 are commonly used in low-power applications (e.g., mobile phones). AIDs of categories 1 and 3 are commonly used in medium and high-power applications. Though AIDs of categories 1 and 2 often include non-linear components that may cause non-linear effects during emission, we assume that the AT behaves, with respect to its radio port and antenna port, substantially as a passive linear 2-port device.

We use Z_{Sant} to denote the impedance seen by the antenna port, and Z_U to denote the impedance presented by the radio port, which depends on Z_{Sant} and on the impedances of the AIDs. A wanted value of Z_U being denoted by Z_W, the user port tuning range, denoted by $D_{UTR}(Z_W)$, is the set of all Z_{Sant} for which there exist achievable values of the nominal reactances of the AIDs, such that $Z_U = Z_W$, at f_C [8].

In the literature on ATs, "open-loop" often erroneously refers only to a control scheme without SU, so that the AT is typically adjusted only as a function of the operating frequency, which is known to the TSPU [1, § 4.5.1], [9]. In this paper, following normal terminology, "open-loop control" means: control which does not utilize a measurement of the controlled variable [10]. In contrast, "closed-loop control" (which is also referred to as "feedback control") means control in which the control action is made to depend on a measurement of the controlled variable, a definition which does not imply that the control action repetitively or continuously depends on a repetitive or continuous measurement of the controlled variable.

In what follows, "model-based" refers to a control scheme which uses a model that describes relevant properties of the AT and the CU, and a single sample of each of the one or more sensing unit output signals, to obtain nominal AID reactance values intended to provide the wanted adjustment of the AT.

III. Type 0 Control schemes

Type 0 designates the open-loop AT control schemes which do not use any SU. In subtype *a* of type 0, the nominal reactance (or an equivalent variable) of each AID is determined only as a function of an operating frequency, typically by utilizing a lookup table, the entries of which have for instance been determined based on experiments. In subtype *b*, the nominal reactance of at least one AID (or an equivalent variable) is determined as a function of an operating frequency and of at least one auxiliary variable which is assumed to be correlated with some electromagnetic characteristics of the surroundings of the transmitter. In a mobile phone, such an auxiliary variable may for instance be [11]:

- a localization variable determined by a localization sensor, which is assumed to depend on a distance between a part of a human body and a zone of the transmitter;
- a communication type variable that indicates whether a radio communication session is a voice session or a data session; or
- a speakerphone mode activation indicator or a speaker activation indicator; etc.

The idea of subtype *b* is that such auxiliary variables can be used to mitigate the EECS, statistically, if a correlation exists between the operating frequency and the one or more auxiliary variables on the one part, and optimal nominal reactance values on the other part. In practice, the nominal reactance values (or equivalent variable values) may be obtained from a lookup table, as a function of the operating frequency and of a typical use configuration determined based on the one or more auxiliary variables.

IV. Type 1 Control schemes

Type 1 designates the control schemes which use the configuration of Fig. 1(a) and are such that the TCSs are determined by a feedback control system which seeks to obtain a wanted value of Z_U, denoted by Z_W, without being a Type 2 control scheme presented in Section V. Typically, the TSPU estimates q real quantities depending on Z_U, and q is often equal to two. We can identify 3 subtypes. Subtype *a* designates the schemes using continuous-time control, such as the ones described in [3], [5, § IV-A] and [12]-[14]. Subtype *b* designates the non-model-based schemes which utilize discrete-time control, such as the schemes described in [5, § IV-B] and [15]-[17]. Subtype *c* designates the model-based discrete-time control schemes, such as the ones described in [18]-[22].

In practice, a type 1 control scheme is designed for a particular AT structure. For subtypes *a* and *b*, the reactance of each AID is typically determined by a separate feedback control loop which uses one of the q real quantities depending on Z_U as feedback signal. For instance, let us assume that the AT has the L-network structure shown in Fig. 2, in which the variable parallel

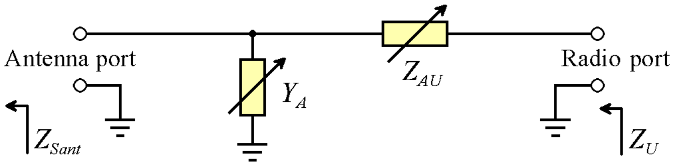

Fig. 2. An AT having a L-network structure.

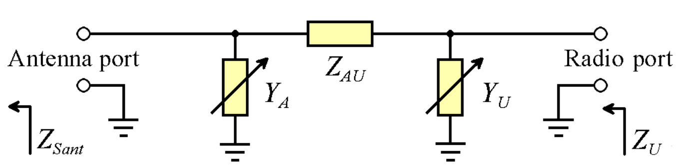

Fig. 3. An AT having a π-network structure.

admittance Y_A and the variable series impedance Z_{AU} each correspond to an AID [23]. If we ignore losses in the AT, we have, at the frequency f_C,

$$Z_U = \frac{1}{\frac{1}{Z_{Sant}} + jB_A} + jX_{AU} \qquad (1)$$

where the real susceptance B_A and the real reactance X_{AU} are such that $Y_A = jB_A$ and $Z_{AU} = jX_{AU}$. Let us assume that Z_W is real. Since $\partial Z_U / \partial X_{AU} = j$, an inner feedback loop using $\mathrm{Im}(Z_U)$ or $\arg(Z_U)$ as feedback signal may easily be designed to provide a zero $\mathrm{Im}(Z_U)$. At the frequency f_C and ignoring losses, we have

$$\mathrm{Re}(Z_U) = \frac{G_{Sant}}{G_{Sant}^2 + \left(B_{Sant} + B_A\right)^2} \qquad (2)$$

where the real conductance G_{Sant} and the real susceptance B_{Sant} are such that $G_{Sant} + jB_{Sant} = 1/Z_{Sant}$. It follows that $Z_U = Z_W$ is possible only if $\mathrm{Re}(Z_W) \leq 1/G_{Sant}$, and that

$$\frac{\partial\, \mathrm{Re}(Z_U)}{\partial B_A} = \frac{-2G_{Sant}\left(B_{Sant} + B_A\right)}{\left[G_{Sant}^2 + \left(B_{Sant} + B_A\right)^2\right]^2} \qquad (3)$$

Thus, if the antenna and the AIDs are such that the sign of $B_{Sant} + B_A$ is known by design, an outer feedback loop using $k\,\mathrm{Re}(Z_U)$, where k is real, as feedback signal may be designed to provide $\mathrm{Re}(Z_U) = \mathrm{Re}(Z_W) = Z_W$. Also, if the outer feedback loop is made much slower than the inner feedback loop, $k\,|Z_U|$ may be used as a feedback signal of the outer feedback loop.

If the sign of $B_{Sant} + B_A$ is not known, a stable subtype *a* or *b* control scheme is more difficult to design for the AT shown in Fig. 2. For instance, a possible route would be to ensure that, when the control system is switched on, $B_{Sant} + B_A$ has always the wanted sign, so that this sign would be maintained thereafter by the feedback control system, provided B_{Sant} and f_C never vary too rapidly, and provided Z_{Sant} remains in or close to the user port tuning range $D_{UTR}(Z_W)$ of the AT at f_C.

Let us now consider a subtype *a* or *b* control scheme using the AT shown in Fig. 3, which has a π-network structure [23]-[24]. Here, the series impedance Z_{AU} is fixed, and the variable parallel admittances Y_A and Y_U each correspond to an AID. If we ignore losses in the AT, we have, at the frequency f_C,

$$\frac{1}{Z_U} = \frac{1}{\frac{1}{\frac{1}{Z_{Sant}} + jB_A} + jX_{AU}} + jB_U \qquad (4)$$

where the real susceptance B_U is such that $Y_U = jB_U$. Since $\partial(1/Z_U)/\partial B_{AU} = j$, an inner feedback loop using $\mathrm{Im}(1/Z_U)$ or $\mathrm{Im}(Z_U)$ or $\arg(Z_U)$ as feedback signal may be designed to provide a zero $\mathrm{Im}(1/Z_U)$. However, the reader can easily check that $\partial \mathrm{Re}(1/Z_U)/\partial B_{AU}$ and $\partial \mathrm{Re}(Z_U)/\partial B_{AU}$ are involved, so that a stable subtype *a* or *b* control scheme is difficult to design for the AT shown in Fig. 3.

The error of a subtype *b* control scheme is determined in subsection *B* of the Appendix.

For subtype *c*, the control scheme is based on a model of the AT and CU. For instance, let assume that the AT is the one shown in Fig. 3, that the nominal reactance of any one of the AIDs is determined by an adjustment instruction received by the CU from the TSPU, and that the absolute value and the phase of Z_U have been estimated, at f_C, for nominal AID reactances determined by an initial adjustment instruction [21]-[22]. In a first step, using the model and the initial adjustment instruction, the TSPU can estimate Y_A and Y_U, and then estimate Z_{Sant} using

$$\frac{1}{Z_{Sant}} = \frac{1}{\frac{1}{\frac{1}{Z_U} - Y_U} - Z_{AU}} - Y_A \qquad (5)$$

If the estimated Z_{Sant} lies in or close to the user port tuning range $D_{UTR}(Z_W)$ of the AT at f_C, the TSPU can, in a second step, compute a subsequent adjustment instruction such that, according to the model, Z_U is close to Z_W. This computation may for instance use the fast algorithm proposed in [25, Appendix C], which takes losses in the AID into account. The operation of the control system may stop at this point, so that the nominal AID reactances directly jump from the ones determined by the initial adjustment instruction, to the ones determined by the subsequent adjustment instruction, by utilizing the model twice.

If the model of the AT is not accurate, the subsequent adjustment instruction may produce a Z_U which is not close to Z_W. The error of a subtype *c* control scheme is determined in subsection *E* of the Appendix. In practice, one or more lookup tables are needed to obtain an accurate model. Additionally, some of the computations can be replaced with interpolations, if a suitable lookup table, or a suitable set of lookup tables, is provided.

For AIDs having a finite set of nominal reactance values (AIDs of category 1), subtype *b* control schemes using digital processing, or subtype *c* control schemes are preferred.

V. TYPE 2 CONTROL SCHEMES

Type 2 designates the control schemes which use the configuration of Fig. 1(a) and in which the TSPU uses extremum-seeking control to obtain that Z_U approximates a wanted value Z_W. Extremum-seeking control is a family of nonlinear control methods whose purpose is to autonomously find either a maximum or a minimum of a performance variable, the performance variable being a real function of one or more outputs of a controlled system, by controlling one or more inputs of the controlled system. In an extremum-seeking control algorithm, one or more signals varying over time are caused to appear at these one or more inputs of the controlled system, in a way that allows the algorithm to probe the nonlinearity of the performance variable with respect to the one or more inputs of the controlled system, and to get closer to an extremum. Thus, extremum-seeking control algorithms are based on the information that the extremum exists, but they do not need an exact knowledge of the controlled system to find the extremum. For this reason, extremum seeking control is said to be a non-model-based real-time optimization approach. A type of extremum-seeking control which uses one or more periodical perturbations is usually referred to as perturbation based extremum-seeking control [26]. There are many other types of extremum-seeking control, such as sliding mode extremum-seeking control, neural network extremum-seeking control, relay extremum seeking control, perturb and observe, numerical optimization based extremum-seeking control, stochastic extremum-seeking control, etc [27]-[29].

In an automatic AT control scheme, the nominal reactances of the one or more AIDs may be regarded as the "one or more inputs of the controlled system". Thus, the extremum-seeking control algorithm controls and varies the AID reactances over time, to get closer to an extremum of the performance variable.

The performance variable may be substantially the absolute value of the reflection coefficient at the radio port, or any monotone function of this quantity [29, ch. 7], [30]-[33]. The absolute value of the reflection coefficient is a performance variable which typically varies very little far from the sought global minimum, and which may present several local minima at a given frequency. Thus, a type 2 control scheme must be designed to avoid that the extremum-seeking control algorithm fails to converge, or converges to a local extremum which is not the wanted global extremum. For this reason, in a typical type 2 control scheme, suitable initial values of the nominal AID reactances are generated before extremum seeking starts, as a function of f_C, using one of the type 0 control schemes.

It is useful to identify 2 subtypes. Subtype *a* designates the schemes using continuous-time extremum-seeking. Subtype *b* designates the schemes using discrete-time extremum-seeking, such as the schemes described in [30]-[33]. For subtype *b*, the error is computed in subsection *B* of the Appendix. It is worth mentioning that subtype *b* includes a brute force extremum seeking technique applicable to the case where each AID can provide a finite (and small) number of nominal reactance values: all combinations of AID reactance values are tested, and a combination providing either the larger or the smaller value of the performance variable is selected [34]-[36]. This approach does not use initial values of the nominal AID reactances, determined as a function of f_C.

VI. Type 3 Control schemes

Type 3 designates the model-based control schemes which use the configuration of Fig. 1(b) and are such that: the TSPU estimates q real quantities depending on Z_{Sant}; and the nominal reactance (or an equivalent variable) of at least one AID is determined as a function of f_C and of these real quantities, using a model of the AT. Typically, $q = 2$ [37] [38]. Since type 3 is an open-loop control scheme, an accurate knowledge of the characteristics of the AT is essential for good results. If these characteristics depend on temperature, it is advantageous to take into account one or more temperatures in the AT to determine the TCSs [39]. The aim of a type 3 control scheme is unconstrained.

If the aim of the control scheme is to obtain a wanted value Z_W of Z_U, we observe that the type 3 control scheme has much in common with the second step of the operation of a type 1 subtype *c* control scheme, presented above in Section IV. For instance, in the case of an AT having the structure of a π-network, suitable TCSs may be determined using the iterative computation technique of [25, Appendix C] or a numerical algorithm that minimizes a suitable performance variable, for instance $|Z_U - Z_W|^2$ computed using the model of the AT. A detailed algorithm which directly takes into account the set of the nominal reactance values of the AIDs has been disclosed [40].

The error of a type 3 control scheme is determined in subsection *D* of the Appendix. This errors depends on the accuracy of the model.

If the aim of the control scheme is to maximize the average power delivered by the antenna port, denoted by P_{Sant}, suitable TCSs may be determined using a numerical algorithm that maximizes this output power, computed using the model.

For any aim of the control scheme, some or all of the computations can be replaced with interpolations, if a suitable lookup table is provided.

VII. Type 4 Control schemes

Type 4 designates new control schemes which use the configuration of Fig. 1(b) and are such that [41] [42]:

- an initial value of each nominal AID reactance is generated, using open-loop control; and
- to increase as much as possible the average power delivered by the antenna port, denoted by P_{Sant}, one or more subsequent values of one or more of the nominal AID reactances are generated, using an extremum-seeking control algorithm.

Generating initial nominal AID reactance values which are not too far from the one that would maximize P_{Sant} has two advantages: it avoids that the extremum-seeking control algorithm converges to a local extremum which is not the wanted global extremum, and it speeds up this convergence, for a given accuracy. For subtype *a*, the initial nominal AID reactance values are obtained as a function of f_C, using one of the type 0 control schemes. For subtype *b*, the initial nominal AID reactance values are obtained as a function of f_C and of real quantities depending on Z_{Sant}, using a type 3 control scheme.

The extremum-seeking control algorithm seeks to maximize or to minimize a performance variable estimated as a function of one or more sensing unit output signals. To discuss possible performance variables, let $s_E(t)$ be the complex envelope of the excitation, $s_O(t)$ be the complex envelope of an electrical variable (voltage, current, incident voltage, etc) sensed at the output port, and f be a function which is differentiable and strictly monotone over the set of positive real numbers.

If the excitation is not amplitude modulated, that is to say if $|s_E(t)|$ is constant, it is easily seen that a possible performance variable is $f(|s_O(t)|)$. For instance, if f is an increasing function, maximizing $f(|s_O(t)|)$ clearly maximizes P_{Sant}.

If the excitation is amplitude modulated, this approach does not work, because a variation in $|s_E(t)|$ creates a variation in $f(|s_O(t)|)$. In this case, we may consider that, for given values of Z_{Sant} and of the AID reactances, $s_E(t)$ is substantially proportional to a modulating signal $s_M(t)$ so that $|s_O(t)|$ is substantially equal to $\lambda\,|s_M(t)|$, where λ is a real gain. Here, a possible performance variable is $f(|s_O(t)|)/f(|s_M(t)|)$, provided f is such that, for any positive λ, the ratio $f(\lambda|s_M(t)|)/f(|s_M(t)|)$ is independent of $|s_M(t)|$. The function f must therefore be such that, for any positive λ and for any positive x, we have

$$\frac{f(\lambda x)}{f(x)}=\frac{f(\lambda)}{f(1)} \tag{6}$$

so that

$$f(\lambda x)=\frac{f(x)f(\lambda)}{f(1)} \tag{7}$$

Taking a partial derivative of (7) with respect to x, and a partial derivative of (7) with respect to λ, we obtain

$$\frac{f'(x)f(\lambda)}{\lambda\, f(1)}=\frac{f(x)f'(\lambda)}{x\, f(1)} \tag{8}$$

in which f' is the derivative of f. For $\lambda = 1$, we obtain the differential equation

$$\frac{f'(x)}{f(x)}=\frac{1}{x}\frac{f'(1)}{f(1)} \tag{9}$$

This is not a linear differential equation. However, if we first consider that $k = f'(1)/f(1)$ is an arbitrary variable, we can integrate the resulting first-order linear differential equation of parameter k. This allows us to find that the solutions of (9) are the functions which satisfy

$$f(x)=K\,x^k \tag{10}$$

where k and K are real constants, K being nonzero. Conversely, all functions given by (10) satisfy (6), and are strictly monotone for k nonzero. Thus, for an amplitude modulated excitation, the suitable functions f are given by (10) where k and K are nonzero real constants.

Ideally, a type 4 control scheme maximizes P_{Sant} with respect to the reactances of the AIDs. This maximization does not entail conjugate matching at the antenna port of the antenna tuner (as opposed to a maximization of P_{Sant} with respect to the resistance and the reactance seen by the antenna port).

If the radio port sees a linear source of impedance Z_S, an ideal type 4 control scheme maximizes the transducer power gain of the AT at f_C. If the AT is a part of a transceiver using TDD, what was said above applies to emission. In this case, if we further assume that the AT is reciprocal with respect to its radio port and antenna port, and that the radio port sees a linear load of impedance Z_S during reception, it follows from a well-known reciprocal power theorem proven by Kurokawa [43, § IV] that the AT adjustment obtained for emission maximizes the transducer power gain of the AT during reception.

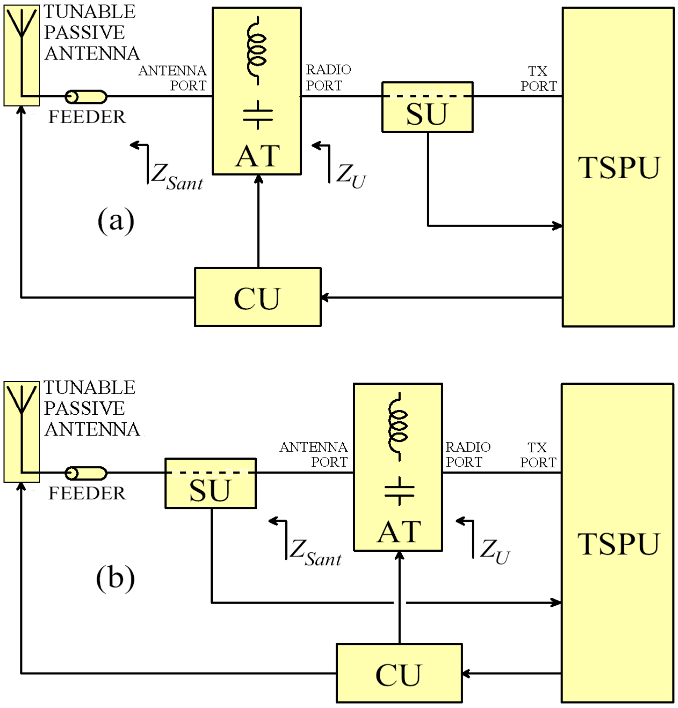

Fig. 4. Two possible configurations of a transmitter comprising a tunable passive antenna, an antenna tuner (AT), a sensing unit (SU), a control unit (CU) and a transmission and signal processing unit (TSPU).

VIII. Other Control Schemes

We have defined five types of control schemes which can be used to automatically adjust an AT of a wireless transmitter. They cover most schemes described in the literature, but not all of them.

First, some AT control schemes use more than one SU, for instance: one SU at the radio port and one SU inside the AT [6], [44]; or one SU at the radio port and another at the antenna port [45]-[46]. Many variations are possible.

Second, an AT may be used in conjunction with a tunable passive antenna (TPA), as shown in Fig. 4, to obtain a broader tuning range than the one provided by the AT alone, and to reduce feeder losses [47]-[50]. An adjustment of a TPA may provide a change in its directivity pattern, and/or a change in its impedance. If the TPA is such that adjusting it produces a change in its impedance, an automatic control system may use the adjustment of the TPA to obtain a coarse adjustment of Z_{Sant}, and then use the AT to obtain a fine adjustment, using any one of the five types of control schemes.

Here, it is worth noting that some authors strangely refer to the adjustment of a TPA as "aperture tuning", and to the adjustment of an AT as "impedance tuning".

IX. Qualitative Comparison of the Control Schemes

A. Closed-loop versus open-loop

Since an extremum-seeking control algorithm is based on closed-loop control, we can say that types 1, 2 and 4 utilize closed-loop control, whereas type 0 and type 3 only utilize open-loop control. A remarkable characteristic of a typical AT control system is the severe non-linearity of the equations that govern the AT, for instance visible in (1)-(4). The relation between the reactance of an AID and the TCS(s) it receives is typically also involved. For these reasons, a continuous-time (analog) closed-loop control system, if started far from its goal, is typically unable to reach it, or to reach it in a reasonable time. Consequently, we may assume that practical type 1 and type 2 control schemes include a preliminary open-loop step, of type 0. Type 4 always includes a preliminary open-loop step, of type 0 or type 3. Thus, most current closed-loop control designs use digital circuits and lookup tables, because they are unavoidable for an open-loop control step; and closed-loop control systems without digital circuits (which can only be of type 1 subtype *a* or type 2 subtype *a*) are outdated for most applications.

B. Measurements and mitigation of EECS

The requirements on the SU and the processing of sensing unit output signals are different for each control scheme, as shown in Table I. The easiest measurements are: the scalar reflection coefficient measurements at the radio port, used in type 2, which need only be accurate in the vicinity of $Z_U = Z_W$ if an effective preliminary open-loop step has been used; and the scalar measurements at the antenna port, used in type 4 subtype *a*, which can be relative voltage or current measurements, since they are only used to find a maximum power. Vector impedance measurements at the radio port, used in type 1, are more involved, but they need only be accurate in the vicinity of $Z_U = Z_W$ if an effective preliminary open-loop step has been used. Vector impedance measurements at the antenna port, used in type 3 and type 4 subtype *b*, are the most challenging, because accuracy is needed in the entire set of possible values of Z_{Sant}.

As shown in Table I, a mitigation of the EECS is obtained with all schemes, except type 0.

C. Aim of the control scheme and design goal

The aims of the different control schemes are shown in Table I. How do these aims correspond to possible design goals?

Let us for a while assume that the design goal is a maximization of P_{Sant}, in a context where the TX port of the TSPU need not be linear, and where the SU is transparent to the signals intended for the antenna. In the case of a lossless AT, the average power delivered by the TX port is equal to P_{Sant}, so that a maximum power delivered by the TX port (if the TX port was linear, this would imply a conjugate matching at the TX port) corresponds to a maximum P_{Sant}. In this case, a type 1, 2 or 3 control scheme, configured to provide a value of Z_U which maximizes the power delivered by the TX port at f_C (we assume that this value is known), maximizes P_{Sant}, like a type 4 control scheme. If losses in the AT are not very small, a maximum power delivered by the TX port need not correspond to a maximum P_{Sant}, so that the types 1, 2 and 3 control schemes considered above are not optimal for the design goal, while type 4 is optimal.

The possible optimization of TDD reception, explained in Section VII, is another advantage of the type 4 control scheme.

Let us now assume that the design goal is $Z_U = Z_W$, for instance because it provides a wanted linearity or spectral purity, or a wanted efficiency of a power amplifier, or simply because Z_W is the nominal load of the TX port. Here, a type 1, 2 or 3 control scheme can be optimal, if it is configured to provide $Z_U = Z_W$, while a type 4 control scheme is not optimal for the design goal (except in the case of a lossless AT).

D. Accuracy, speed and dependence on a model of the AT

The performance of a control system depends on many implementation details. However, as a guideline, Table I indicates the relative accuracy and speed of the different control systems, based on the following considerations:

- all schemes using only open-loop control are very fast, but cannot be very accurate, because their accuracy depends on a model of the AT, and models are imperfect;
- all schemes using closed-loop control are very accurate, but type 1 subtype *c* is special;

TABLE I

SOME POSSIBLE CHARACTERISTICS OF THE AT CONTROL SCHEME TYPES AND SUBTYPES DEFINED IN THE PAPER

Type	Figure	Subtype	Measurement	Mitigation of EECS	Aim of control	Accuracy	Speed
0		*a*	none	no	any	poor	very fast
		b	auxiliary variable	limited	any	poor	very fast
1	1(a)	*a*	vector at radio port	yes	$Z_U = Z_W$	very good	slow / fast
		b	vector at radio port	yes	$Z_U = Z_W$	very good	fast
		c	vector at radio port	yes	$Z_U = Z_W$	good	very fast
2	1(a)	*a*	scalar at radio port	yes	$Z_U = Z_W$	very good	very slow / medium
		b	scalar at radio port	yes	$Z_U = Z_W$	very good	medium
3	1(b)		vector at antenna port	yes	any	good	very fast
4	1(b)	a	scalar at antenna port	yes	maximizing P_{Sant}	very good	medium
		b	vector at antenna port	yes	maximizing P_{Sant}	very good	very fast

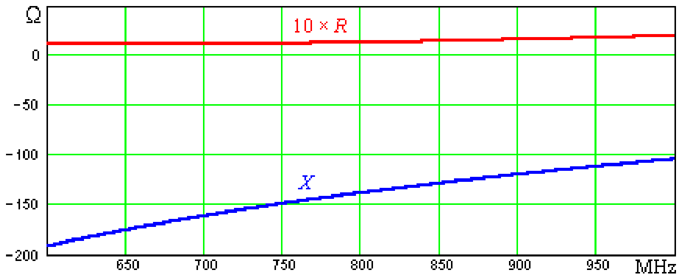

Fig. 5. Real part R and imaginary part X of the impedance seen by the antenna port, for $d = 0.1$ m.

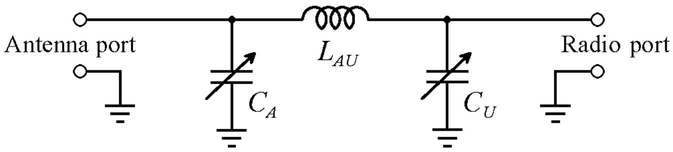

Fig. 6. An AT having a π-network structure.

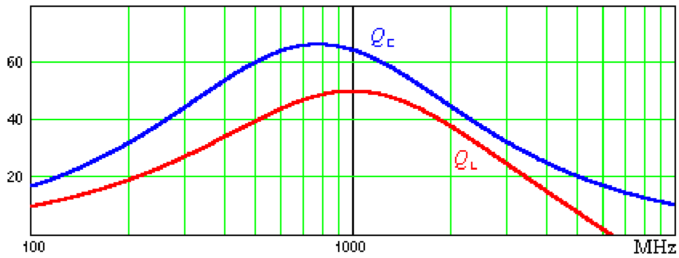

Fig. 7. Quality factor Q_L of the coil and quality factor Q_C of each adjustable impedance device, for the AT of Section V.

- the schemes using closed-loop discrete-time control are supposed to include a preliminary open-loop step, so that the characteristics of the open-loop and closed-loop steps interact to provide the accuracy and the speed of the schemes;
- if they do not include a preliminary open-loop step, the schemes using closed-loop continuous-time control (type 1 subtype *a* and type 2 subtype *a*) are slow at best; in the opposite case, their speed is similar to the one of the closed-loop discrete-time control scheme of same type;
- all schemes using closed-loop control are significantly slower than open-loop scheme, but type 4 subtype *b* is special, because it includes an accurate and very fast preliminary type 3 step, so that a value of P_{Sant} which is very close to the aimed maximum value is obtained very quickly;
- type 2 subtype *a* is slower than type 1 subtype *a*, and type 2 subtype *b* is slower than type 1 subtype *b*, because in the type 2 schemes, a non-model-based extremum-seeking control algorithm must probe the non-linearity of the performance variable, so that it follows an indirect path toward its aim.

According to the definition of Section II, the model-based control schemes are type 1 subtype *c*, type 3 and type 4 subtype *b*. The subtypes *a* and *b* of type 1 are non-model-based, even though they use a model of the AT, to determine in which direction the nominal reactance of each AID must vary, in order to move from the current value of Z_U toward Z_W. All model-based control schemes are very fast. They are computationally demanding, in particular type 1 subtype *c*, because it uses the model twice.

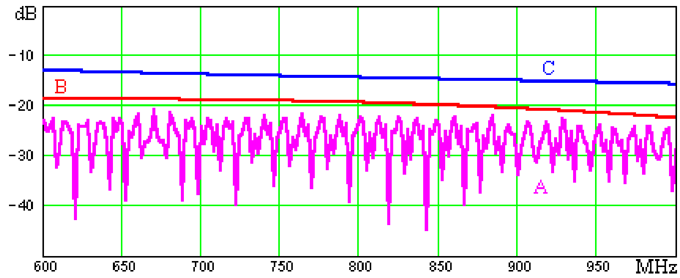

Fig. 8. Reflection coefficient at the radio port versus frequency, for $d = 0.1$ m. Curve A: effect of discretization on type 1, 2 or 3. Curve B: worst case of type 3 with 1% uncertainty. Curve C: type 4.

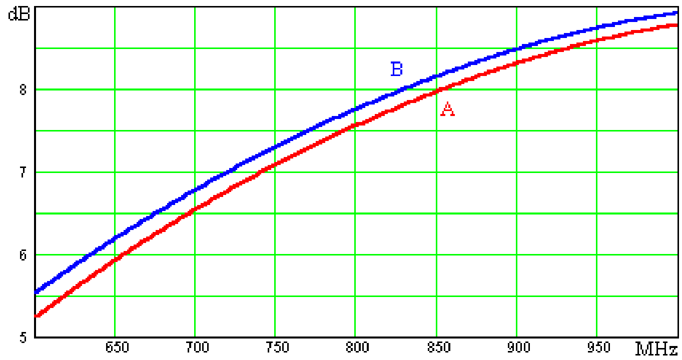

Fig. 9. Insertion gain versus frequency, for $d = 0.1$ m. Curve A: type 1, type 2 or type 3 using an accurate AT model. Curve B: type 4.

X. Example for a Quantitative Comparison

We are going to investigate several antenna tuner control schemes, implemented on a theoretical system comprising a 74.9-mm-long dipole antenna, used in the frequency range 600 MHz to 1 GHz, a lossy feeder, and the AT shown in Fig. 6, which consists of a coil and two AIDs each presenting a negative reactance. The investigated configuration also included a large plate made of a perfect electrical conductor (PEC) lying parallel to the antenna, at a distance d of the antenna, used to create and vary the EECS. The impedance Z_{Sant} presented by the antenna and the feeder varies as a function of the frequency and of d. The computed values of Z_{Sant} for $d = 0.1$ m are shown in Fig. 5.

We use the coil model presented in [25, § 5] with $L_N = 10$ nH, $R_S \approx 641$ mΩ, $R_P \approx 6.74$ kΩ and $C \approx 63.4$ fF. Fig. 7 shows the quality factor Q_L of the coil. We use the AID model of [25, § 5], with $\omega_P = 37 \times 10^6$ rd/s and $\omega_S = 650 \times 10^9$ rd/s. According to this model, the quality factor is independent of the capacitance value. Fig. 7 shows the quality factor Q_C of the AIDs. We also assume accurate sensing unit output signals, and an accurate analog or digital signal processing.

Let us look at the value of Z_U provided by the different types of control schemes. Types 1 and 2 can exactly provide $Z_U = Z_W$, if each AID is continuous (i.e., if its set of nominal reactance values is an interval). The same applies to a type 3 control scheme aiming $Z_U = Z_W$, if, in addition, it uses an exact model of the AT. In Fig. 8, we assume $Z_W = 50$ Ω, and we show the reflection coefficient, defined with respect to Z_W, after automatic adjustment of the AT. For types 1, 2 and 3, Fig. 8(A) shows the effect of a discretization of the capacitance values (64 logarithmically spaced nominal values for C_A and C_U), in the case of category 1 AIDs. For type 3 and continuous AIDs, Fig.

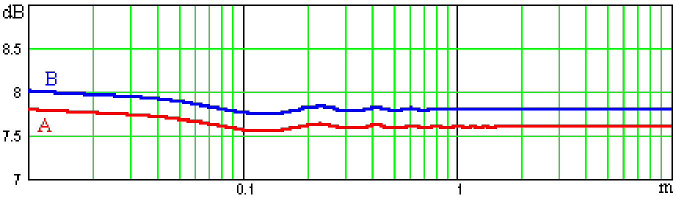

Fig. 10. Insertion gain versus d, at 800 MHz. Curve A: type 1, type 2 or type 3 using an accurate AT model. Curve B: type 4.

8(B) shows the effect of an inaccurate AT model (1% uncertainty of the nominal values for C_A and C_U). The result for type 4 and continuous AIDs are shown in Fig. 8(C).

In Fig. 9 and Fig. 10, we assume that the TX port is linear and presents an impedance of 50 Ω, we assume continuous AIDs, and we show the insertion gain of the AT, i.e., the ratio of the power delivered by the antenna port of the automatically adjusted AT, to the power received by the feeder if it was directly coupled to the TX port. For type 3, we also assume an exact model of the AT. Type 4 maximizing the power delivered by the antenna port, the plots show that type 1, 2 and 3 are not optimal, by an amount ranging from about 0.14 dB to 0.29 dB in this example.

Let us have a closer look at type 4. The maximum reflection coefficient shown in curve C of Fig. 8 is about –12.9 dB, corresponding to a VSWR of about 1.58. The power amplifier of a typical transmitter operates without problem with a VSWR less than 2. Assuming that this is the case for our transmitter, a type 4 control scheme can be used, and provides a more efficient transmitter than the other types, as shown in Fig. 9 and Fig. 10.

XI. Conclusion

Five types of control scheme applicable to a single-antenna-port and single-radio-port antenna tuner have been presented. They have been compared as regards: their use of closed-loop control and/or open-loop control; the measurements used (which impacts the cost); their ability to mitigate the EECS, which include the user interaction; the aim of the control scheme and how it relates to a design goal; their accuracy and speed; and their dependence on a model of the AT and CU.

The new type 4 control scheme provides the best transmitter efficiency, because the aim of this scheme is maximizing P_{Sant}, and it is accurate. It leaves a residual VSWR, which should be small enough. Type 4 subtype *a* is inexpensive (because it uses scalar measurement), but not fast. Type 4 subtype *b* is more expensive, but very fast. However, the fastest schemes providing a good efficiency are type 1 subtype *c*, and type 3. For these model-based schemes, it is advisable to take into account one or more temperatures in the AT to determine the TCSs.

Appendix

A. Purpose of this appendix and notations

We consider a control scheme which seeks to obtain that Z_U at f_C is very close, or as close as possible, to a wanted impedance Z_W. We want to further explain, and derive the error of, the different relevant types of control scheme.

We need to clarify the meaning of "very close, or as close as possible, to a wanted impedance Z_W". Let us chose a complex function of a complex variable, denoted by h, the function being continuous and smooth where it is defined, and such that $h(Z_W) = 0$. For instance, the function may be defined by

$$h(Z) = Z - Z_W \tag{11}$$

or by

$$h(Z) = Z^{-1} - Z_W^{-1} \tag{12}$$

or by

$$h(Z) = (Z - Z_W)\,(Z + Z_W)^{-1} \tag{13}$$

We say that Z is (very) close to Z_W if and only if $h(Z)$ is (very) close to zero; we say that Z is as close as possible to Z_W if and only if $h(Z)$ is as close as possible to zero; etc.

We assume a digital control system in which the nominal reactances (or equivalent variables) of the AIDs are, at a given point in time, determined by the CU as a function of a tuning unit adjustment instruction delivered by the TSPU. An exact numerical model of the AT and of the CU may be put in the form of a mapping denoted by g_{EU} and defined by

$$g_{EU}\,(f, Z_{Sant}, t_C, \mathbf{a}_T) = Z_U \tag{14}$$

where f is the frequency, where t_C is the applicable tuning unit adjustment instruction, and where $\mathbf{a}_T$ is a real vector of temperatures, which is sufficient to characterize the effects of temperature on Z_U. As an example, if the impedance of each AID depends on its temperature and if the characteristics of the CU do not significantly depend on temperature, the elements of $\mathbf{a}_T$ could be the temperatures of the AIDs.

At the frequency f and for the temperatures specified in $\mathbf{a}_T$, the user port impedance range of the antenna tuner is given by

$$D_{UR}(Z_{Sant}) = \{g_{EU}\,(f, Z_{Sant}, t_C, \mathbf{a}_T) \mid t_C \in T_C\} \tag{15}$$

where T_C is the set of the possible tuning unit adjustment instructions [8].

B. Non-model-based digital closed-loop control schemes

In a non-model-based digital closed-loop control scheme (that is, a type 1 subtype *b* or type 2 subtype *b* scheme), a full automatic adjustment of the AT requires several iterations, each iteration comprising the following steps: applying an excitation to the radio port; sensing electrical variables; delivering an adjustment instruction; and delivering TCS. After a sufficient number of iterations, a final tuning unit adjustment instruction t_{CF} is reached. If the control scheme is well-designed, the measured value of Z_U at f_C and after t_{CF}, denoted by Z_{UM}, satisfies

$$Z_{UM} \approx Z_W - d_{QCL1}\,(f_C, Z_{UM}, t_{CF}, \mathbf{a}_{TM}) \tag{16}$$

where the mapping d_{QCL1} represents a quantization error which is known to the control system, but which cannot be avoided because there is no t_C in T_C such that Z_{UM} is closer to Z_W. Thus, the error of the control system is given by

$$Z_U - Z_W \approx Z_U - Z_{UM} - d_{QCL1}\,(f_C, Z_{UM}, t_{CF}, \mathbf{a}_{TM}) \tag{17}$$

where $Z_U - Z_{UM}$ is the measurement error.

C. Additional assumptions for model-based control schemes

In a model-based digital control scheme (that is, a type 1 subtype *c* or type 3 scheme), we assume that the TSPU, instead of knowing the exact numerical model of the AT and of the CU, corresponding to g_{EU}, knows an approximate numerical model which corresponds to a mapping g_{AU} such that

$$g_{AU}(f, Z_{Sant}, t_C, \mathbf{a}_T) + d_{AU}(f, Z_{Sant}, t_C, \mathbf{a}_T) = Z_U \tag{18}$$

where the mapping d_{AU} represents the error of the approximate numerical model, and is not known to the control system.

D. Type 3 control scheme

A type 3 control scheme uses a measurement Z_{SantM} of Z_{Sant} at f_C, and possibly a measurement $\mathbf{a}_{TM}$ of $\mathbf{a}_T$. Here, a suitable algorithm is used to find a tuning unit adjustment instruction, denoted by t_{CS}, such that $g_{AU}(f_C, Z_{SantM}, t_{CS}, \mathbf{a}_{TM})$ is very close, or as close as possible, to the wanted impedance Z_W. We write

$$g_{AU}(f_C, Z_{SantM}, t_{CS}, \mathbf{a}_{TM}) + d_{QOL}(f_C, Z_{SantM}, t_{CS}, \mathbf{a}_{TM}) = Z_W \tag{19}$$

where the mapping d_{QOL} represents a quantization error which is known to the control system, but which cannot be avoided because there is no t_C in T_C such that $g_{AU}(f_C, Z_{SantM}, t_{CS}, \mathbf{a}_{TM})$ is closer to Z_W. The resulting Z_U is given by

$$g_{AU}(f_C, Z_{Sant}, t_{CS}, \mathbf{a}_T) + d_{AU}(f_C, Z_{Sant}, t_{CS}, \mathbf{a}_T) = Z_U \tag{20}$$

Thus, the error of the control system is given by

$$\begin{aligned} Z_U - Z_W = {} & g_{AU}(f_C, Z_{Sant}, t_{CS}, \mathbf{a}_T) \\ & - g_{AU}(f_C, Z_{SantM}, t_{CS}, \mathbf{a}_{TM}) \\ & + d_{AU}(f_C, Z_{Sant}, t_{CS}, \mathbf{a}_T) - d_{QOL}(f_C, Z_{SantM}, t_{CS}, \mathbf{a}_{TM}) \end{aligned} \tag{21}$$

in which the first 2 terms of the left-hand side vanish for exact measurements.

E. Type 1 subtype c control scheme

In a type 1 subtype *c* control scheme, an adjustment sequence comprises the following steps: an initial tuning unit adjustment instruction t_{CI} is delivered by the TSPU; a measurement Z_{UIM} of Z_{UI} at f_C is obtained, where Z_{UI} is the value of Z_U at f_C while t_{CI} is applicable; and a subsequent tuning unit adjustment instruction t_{CS} is computed as explained below, and delivered by the TSPU [21]-[22]. While t_{CI} is applicable, we have

$$g_{AU}(f_C, Z_{Sant}, t_{CI}, \mathbf{a}_T) + d_{AU}(f_C, Z_{Sant}, t_{CI}, \mathbf{a}_T) = Z_{UI} \tag{22}$$

Let $\mathbf{a}_{TM}$ be an estimate of $\mathbf{a}_T$, possibly based on a measurement. The TSPU solves the equation

$$g_{AU}(f_C, Z_{SantE}, t_{CI}, \mathbf{a}_{TM}) = Z_{UIM} \tag{23}$$

with respect to the unknown Z_{SantE}, to obtain an estimated value Z_{SantE} of Z_{Sant}. Thus, we have

$$\begin{aligned} Z_{UI} - Z_{UIM} = {} & g_{AU}(f_C, Z_{Sant}, t_{CI}, \mathbf{a}_T) \\ & - g_{AU}(f_C, Z_{SantE}, t_{CI}, \mathbf{a}_{TM}) \\ & + d_{AU}(f_C, Z_{Sant}, t_{CI}, \mathbf{a}_T) \end{aligned} \tag{24}$$

Z_{SantE} and $\mathbf{a}_{TM}$ are used by a suitable algorithm to obtain t_{CS} such that $g_{AU}(f_C, Z_{SantE}, t_{CS}, \mathbf{a}_{TM})$ is very close, or as close as possible, to the wanted impedance Z_W. We note that this step is similar to the one leading to (19).

We may write

$$g_{AU}(f_C, Z_{SantE}, t_{CS}, \mathbf{a}_{TM}) + d_{QCL2}(f_C, Z_{SantE}, t_{CS}, \mathbf{a}_{TM}) = Z_W \tag{25}$$

where the mapping d_{QCL2} represents a quantization error which is known to the control system, but which cannot be avoided because there is no t_C in T_C such that $g_{AU}(f_C, Z_{SantE}, t_{CS}, \mathbf{a}_{TM})$ is closer to Z_W. The resulting Z_U at f_C while t_{CS} is applicable is given by

$$g_{AU}(f_C, Z_{Sant}, t_{CS}, \mathbf{a}_T) + d_{AU}(f_C, Z_{Sant}, t_{CS}, \mathbf{a}_T) = Z_U \tag{26}$$

Thus, the error of the control system while t_{CS} is applicable is given by

$$\begin{aligned} Z_U - Z_W = {} & g_{AU}(f_C, Z_{Sant}, t_{CS}, \mathbf{a}_T) \\ & - g_{AU}(f_C, Z_{SantE}, t_{CS}, \mathbf{a}_{TM}) \\ & + d_{AU}(f_C, Z_{Sant}, t_{CS}, \mathbf{a}_T) - d_{QCL2}(f_C, Z_{SantE}, t_{CS}, \mathbf{a}_{TM}) \end{aligned} \tag{27}$$

in which the first 2 terms of the left-hand side vanish for exact measurements and an exact numerical model.

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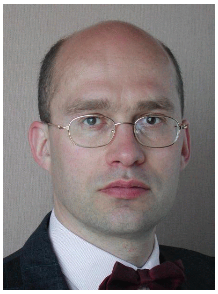
[50] F. Broydé and E. Clavelier, “Method for automatically adjusting a tunable passive antenna and a tuning unit, and apparatus for radio communication using this method,” U.S. Patent 9 991 911, filed Nov. 16, 2017.



Frédéric Broydé (S’84 - M’86 - SM’01) was born in France in 1960. He received the M.S. degree in physics engineering from the Ecole Nationale Supérieure d'Ingénieurs Electriciens de Grenoble (ENSIEG) and the Ph.D. in microwaves and microtechnologies from the Université des Sciences et Technologies de Lille (USTL).

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Dr. Broydé is author or co-author of about 100 technical papers, and inventor or co-inventor of about 80 patent families, for which 45 US patents have been granted. He is a licensed radio amateur (F5OYE).

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Prior to starting Excem in 1988, she worked for Schneider Electrics (in Grenoble, France), STMicroelectronics (in Grenoble, France), and Signetics (in Mountain View, USA).

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