

INTELLIGENT RF RADIO TECHNOLOGY

“The research team is focusing on microwave and radio frequency devices, circuits and systems characterization and modeling because accurate and comprehensive device, circuit and system models are essential for the optimization of the radio frequency front-end performances...”

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HE INTELLIGENT RF RADIO
LABORATORY IS A UNIQUE RESEARCH UNIT
IN THE RF AND WIRELESS COMMUNICATIONS
AREA IN WESTERN CANADA.



<http://www.iradio.ucalgary.ca/>

FADHEL GHANNOUCHI

iCORE Professor

Electrical and Computer Engineering, University of Calgary

The Intelligent RF Radio (iRadio) Lab is devoted to advanced research and development activities pertinent to intelligent RF radio technology applicable to broadband wireless communication systems. The iRadio research program is concerned with RF and microwave devices, circuits and systems; adaptive digital signal processing; modeling of devices, channels and systems; linearization and equalization concepts; space diversity techniques and Multi-Input Multi-Output (MIMO) systems; software-hardware implementation and integration issues; and, other related applications.

EXECUTIVE SUMMARY

This laboratory is positioned at the crossroads of several fields relevant to the highly promising broadband wireless communication systems; and, it is in a position to provide a unique platform for pre-competitive research and for industrial and technological development, while generating close collaboration between university, industry and government researchers working in this promising field.

Although the iRadio Lab was formally launched on November 28th, 2005, it is already staffed with more than ten motivated graduate students and talented researchers, recruited worldwide. The main space dedicated to the iRadio Lab in the University of Calgary's ICT building has been completed, and

an auxiliary space in A Block of the Engineering building allocated for printed circuit board fabrication and circuit prototyping is still under renovation. In addition, the iRadio Lab is in the process of completing the acquisition of advanced equipments for performing high-frequency and high-power linear and nonlinear circuits and systems design, fabrication and characterization. The iRadio Lab facilities are supported by a number of CAD based software tools, test beds and rapid prototyping setups.

Leading-edge research, development, testing, validation, and evaluation of new concepts and architectures pertinent to software-defined and software-enabled RF radio activities are being conducted in collaboration with the RF and wireless communication industries and government research and development agencies. The iRadio Lab has succeeded in the initiation of close formal collaboration with several national and international academic institutions, industry partners and government agencies.

The innovative and applications-oriented research and development activities being carried out at the iRadio Lab have led to more than twenty refereed journal and conference papers and to the development of an innovative technology related to the behaviour modeling of communication systems, which has been disclosed to the university through University Technologies International Inc. (UTI). A website

dedicated to the iRadio Lab (www.iradio.ucalgary.ca) was created and is being used as a tool to disseminate research results and findings.

RESEARCH PROGRAM OVERVIEW

The research team with the iRadio Lab includes 2 faculty members, 1 technical support staff and 1 administrative support staff, 2 research associates, 2 postdoctoral fellows, and 6 graduate students. Five other graduate students are also associated with the iRadio Lab. Alongside the team, formal academic and industrial collaborations are being maintained with École Polytechnique, Montreal; Université de Québec; Université de Tunis, Tunisia; Université de Bordeaux, France; POSTECH, Korea; Mitec Telecom, Canada; Agilent Technologies, USA; Rockwell Collins, USA; TRILabs, Canada; Canadian Space Agency; and Canadian Microelectronic Corporation (CMC).

The main objective of the research team is to target the development of software-enabled, multi-standard, multi-frequency, spectrum-efficient and cost-effective architectures for radio frequencies / digital signal processing (RF/DSP) co-designed linearized power amplifiers / transmitters and MIMO systems for 3G (third generation) and beyond wireless applications. This multidisciplinary research program calls for broad knowledge in the fields of (i)

DSP and mixed signal technology, (ii) microwave technology, and (iii) communications systems, including the implementation and manufacturing processes in these respective fields.

The research program aims to the study of scientific and technical problems related to the characterization and modeling of transistors, amplifiers and transmitters having memory/dispersion effects, in order to develop well thought-out methodologies and approaches leading to the RF/DSP co-design of spectrum-efficient and/or power-efficient transmitters for 3G and beyond wireless applications. The Digital PreDistortion (DPD), Linear amplification with Nonlinear Components (LINC), Envelope Elimination and Restoration (EE&R), and Doherty techniques will be digitally implemented at base band using DSP and Field Programmable Gate Array (FPGA) technologies. Adaptive multi-band reconfigurable receivers using tunable filtering and matching circuits that can be realized either in RF or base band frequencies will be pursued. Development of adaptive algorithms to accurately model and correct for any impairment in the communication link components (transmitter + channel + receiver) will also be targeted. Proof-of-concept prototypes in hybrid and integrated technologies will be designed, manufactured and tested. Communication interface systems with multiple antennas and MIMO technologies will be also investigated, simulated and studied. A 2x2 MIMO prototype will be designed, realized and tested with MC-CDMA and OFDM signals.

The activities planned for the next five years fall into the following research areas:

- Device, system and channel modeling;
- Design of power-efficient power amplifier (PA) modules in hybrid and integrated technologies;
- RF/DSP co-design of DPD, LINC, EE&R, and Doherty-based transmitters;
- Design and emulation of software-controlled and software-enabled transmitters;
- Adaptive multi-band reconfigurable receivers;
- Signal processing techniques for wireless radio systems;
- Realization of prototypes using RF, DSP and FPGA technologies;
- Study, investigation and prototyping of multi-antenna / MIMO radio systems.

- Developing improved methods for characterizing the noise properties of transistors, low-noise amplifiers, and receivers;
- Investigating innovative systems and methods for the characterization of balanced and multi-port devices, for when the design of RF transceivers uses a balanced signalling approach for better noise immunity and spurious rejection.

During the past year, significant findings have been made by the iRadio Lab team related to the accurate characterization of power devices under realistic operation conditions, supporting the development of advanced dynamic and nonlinear behavioural models. This has yielded several publications related to accurate behaviour modeling and pre-correction for the effects of sources of impairments in the transmitter. A disclosure has been filed with UTI to instigate the fulfilment of a patent.

In addition, an accurate extraction technique for hetero-junction bipolar transistors (HBT), small and large signal models has been developed. These models will be used during the next phase of our collaboration with the Canadian Space Agency in the design of power amplification stage of a low-orbit micro-satellite transponder (Quick Sat program). The mid-term objectives in this area will expand the expertise of the team toward the characterization and modeling of balanced devices and circuits.

RESEARCH PROJECTS

1 Microwave and Radio Frequency Devices, Circuits and Systems Characterization and Modeling

The research team is focusing on microwave and radio frequency devices, circuits and systems characterization and modeling because accurate and comprehensive device, circuit and system models are essential for the optimization of the radio frequency front-end performances, from early in the design stage, and the depiction of the most complete picture of how a device / circuit / system will perform in a real operational environment. Among others, the objectives of this research area consist of:

- Researching realistic characterization techniques of radio frequency power devices and amplification stages;
- Advancing device and behavioural models in order to include major physical phenomena;

2 Advanced Power Amplification Systems for 3G and Beyond Applications

Because wireless communication networks have witnessed a virtual explosion in the number of services, accompanied by a migration from single-carrier narrowband

signals toward multi-carrier broadband signals, the research team is focused on advanced power amplification systems. The advancement toward multi-carrier signals calls for the installation and deployment of self-adaptive, high-power and spectrum-efficient transmitters to handle complex modulated signals characterized with a high peak-to-average power ratio over a wide range of environmental and traffic conditions. In particular, the output high-power amplifier is the most power-consuming and costly building blocks of transmitters and has drawn considerable research attention. Research activities in this area aim to:

- Develop advanced multi-branch amplification architecture based, on one or more of the following concepts: Doherty, LINC, EE&R and sigma-delta modulator, to enhance the power efficiency for large back-off operating conditions;
- Investigate advanced linearization techniques to enhance the linearity versus efficiency trade-off;
- Study the potential of the emerging wideband gap devices technologies (silicon carbide and gallium nitride), which are promising large breakthroughs in enabling linear and power-efficient wideband power amplifiers;
- Explore an adaptive bias control based approach to further increase the power-efficiency while the power amplifier is kept in a linear class of operation.

In the last year, the team successfully demonstrated a prototype of a Doherty amplifier that achieved excellent power efficiency when applied to Universal Mobile Telecommunications System (UMTS) signals. An advanced linearization method was developed that, when applied

to the Doherty prototype and driven with wideband signals, showed outstanding linearity and efficiency enhancement. In addition, the team began investigation of the manner in which LINC amplification stage efficiency may be improved in the context of multi-carriers signals.

3 Advanced Adaptive Digital Signal Processing Algorithms for Wireless Transceivers

Research into the design of the digital signal processing module of reconfigurable radios is a critical step since it determines the flexibility, modularity, scalability, and performance of the final design. The partial reconfiguration feature available in the up-to-date DSP and FPGA devices provides a suitable means for the implementation of the signal processing engine needed to handle various modulations schemes employed in different wireless standards while keeping the analog front-end static. In addition, it achieves run-time reconfigurations of the physical layer of the radio

as well as the enhancement of its performances by correcting for the analog front-ends impairments.

In particular, the objectives in this research area are aimed at:

- The development of advanced digital signal pre-processing algorithms, mainly to optimize the trade-off between preserving the signal integrity and improve the power efficiency of analog RF front-ends in wireless transceivers. A major industrial player is highly interested in leveraging these techniques.
- The investigation of a manner through which digital base band modulated signals can be transformed, in order to make use of transmitter architectures that involve high efficiency and nonlinear power stages. This scope is primarily targeted at 3G and beyond wireless communication applications.
- The study of post-processing methods that permit the detection and the correction of the different sources of



Dr Fadhel Ghannouchi

interference effects and the propagation channels in the receiver side.

4 Multi-band, Multi-mode and Multi-antenna SDR based Transmitters

The evolution of wireless communication systems through the continual extension of the old standards (IS95, CDMA2000, UMTS, and WLAN) and/or the introduction of new generations (WiMax, UWB) is bringing about an environment characterized by the coexistence of diverse standards. The research team is considering the variants in terms of standards, frequency bands and output power, leads to a situation where a broad spectrum of base stations and terminals needs to be maintained. In such a context, it is advantageous to shrink the wireless systems spectrum, while still satisfying different needs, by using a flexible architecture for both base stations and user equipment.

The superior reconfigurability of software-defined radios (SDRs) has made them the most promising technology in the realization of such a universal and flexible radio system. Ideally, SDRs require high-speed digital signal processing and high-performance digital-to-analog and analog-to-digital converters, which lead to large power consumption and prohibitive cost. Alternatively, practical software radio suggests the digitization of the signal as early as possible in the receiver chain, while keeping the signal in the digital domain and converting it to the analog domain as late as possible in the transmitter chain. In such a scenario, innovative common multi-band and reconfigurable radio architectures have to be developed while meeting the multidimensional requirements of a heterogeneous wireless networks environment.

Multi-band and reconfigurable transmitters should be combined with a multi-band power amplifier to obtain full benefits of the reconfiguration approach. This research area aims at initiating the development of a multi-standard and multi-frequency high-power and spectrum-efficient power amplification stage. The long-term objective of this research area is to construct multi-band and multi-antenna transceivers for broadband communications.

5 Adaptive and Tunable Receivers

SDRs require particular ultra-low-noise receivers in order to differentiate the desired signal from background noise, blockers and co-channel interferences before the signal reaches the frequency converter. The design of low-noise amplifiers (LNA) is, therefore, very critical; and, particular attention will be paid to the design of multi-band LNA, in order to ensure a low-noise figure over the entire set of targeted centre frequencies. Furthermore, the RF-to-base-band converter is also a critical building block of receivers that must meet stringent linearity requirements. Direct mixing and six-port based receivers, which are currently being envisaged as a promising approach towards configurable receivers, suffer from DC-offset caused by second-order nonlinearity and, consequently, require advanced compensation techniques along with elaborated calibration procedures.

The goals in this area are to build on the research team’s expertise related to non-uniform transmission lines, in order to produce multi-band passive circuits such as multi-band filters and power combiners and to initiate research related to the design of tunable filters and matching circuits that represent the focal point in the design of reconfigurable receivers.



Fadhel Ghannouchi and team members

OBJECTIVES FOR THE NEXT YEAR

Modeling Track

The team plans to continue to work in the behaviour modeling area with more emphasis on developing new behaviour models that can accurately predict the response of strong nonlinear communication systems driven with highly varying envelope and broadband signals, such as MC-CDMA and OFDM to develop and integrate methodology and tools that can be used to characterize, extract the behaviour model parameters and accurately simulate the system. In addition, this methodology has to provide the forward model as well as the reverse model that can be used to pre-compensate for linear and nonlinear distortion in the power amplifier or transmitters, and possibly the whole communication link.

At the device level, more effort will be deployed to develop a scalable equivalent circuit model for HBTs that can be used in designing RF power amplifiers for wireless and satellite communication applications. The group is also planning to study gallium nitride (GaN) devices that will be provided to us by RFHIC, in order to develop accurate and robust equivalent circuit model.

Power Amplifiers Track

Major suppliers of power amplifier/transmitters (PA/Tx) modules have recently pointed out the load-mismatch effects on hand-held and mobile terminal performance, in terms of signal integrity and power efficiency, as a source of undesirable effects that have to be compensated or corrected for at the circuit or system level. It is expected that this effect is more critical for actively loaded amplifiers, such as Doherty amplifiers. Pre-existing work already conducted on Doherty amplifiers will be pushed further, in order to study their sensitivity to load mismatch and to attempt to propose a compensation scheme to avoid significant performance deterioration of the PA.

To increase the power-added efficiency of RF power amplifiers substantially, recent industry directions suggest the move from continuously driven PAs to switched-mode PAs. Therefore, the team is planning to investigate, design and prototype switching mode (class D, class E) and harmonic controlled (class F) PAs. These activities will lead to the selection of the most appropriate configuration to design a medium-power 3G PA for base station applications.

It is well established that LINC-based amplifiers perform badly in terms of power-added efficiency, when driven with highly varying envelope signals such as CDMA and OFDM; the goal for the next year is to begin the investigation of the manner

in which LINC amplifiers' efficiency can be improved in the context of multi-carriers signals. A prototype will be designed and fabricated to carry out the validation of the anticipated scheme / architecture for WiMax access point applications.

Digital Signal Processing for Wireless Communications Track

Work will be continued in the digital predistortion area with more emphasis on developing a new digital RF predistortion technique than can be used on RF amplifiers and repeaters driven by RF signals. This requires the development of new algorithms, or perhaps the adaptation of algorithms already developed, for base band digital predistortion to be used to linearize transmitters driven by base band signals. The synthesis of the digital RF predistortion function necessitates more advanced and recursive adaptive algorithms for identification purposes of the predistortion function.

Peak-to-average power reduction (PAPR) techniques have been proposed and used to "cut" the peaks in the signals without greatly affecting the quality of the signal, in terms of spectral re-growth and error vector magnitude metrics. However, most of these techniques require a "kind" of feedback signal from the receiver, which is not always possible in practical situations. Other objective in this track is the development of a blind PAPR algorithm suitable for WiMAX communications systems.

SDR Transmitters Track

The rationale and one of the important motivations in using SDR based transmitters is their ability to handle simultaneously, and switch between, multiple communication signals using different frequency bands and different types of modulations schemes and standards. To be able to handle such diversity, the RF front-ends have to maintain the performance of the RF chain for all the frequencies / channels concerned. This implies the access and use of multi-standard and multi-frequency high-power amplification stages, as well as multi-band power combiners and matching circuits. During the next year, research projects will investigate possible techniques that can be used to achieve the design of these multi-frequency RF front-end key components.

Adaptive and Tunable Receivers Track

The study and investigation of multi-band RF filters using non-uniform transmissions lines will be initiated next year. In addition, co-simulation and analysis of an RF sub-sampling architecture suitable for multi-standard signals will be also carried out and will be compared to well establish architectures, such as super-heterodyne and direct conversion, in terms of performances and complexity.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

TEAM LEADER

DR FADHEL GHANNOUCHI

Director of iRadio Lab, and (Tier 1) Canada Research Chair

Research interests are in the areas of microwave instrumentation, modeling of microwave devices and communications systems, design and linearization of RF amplifiers and SDR radio systems

Member of College of Reviewers of Canada Research Chairs

Session's Chair and workshop organizer in IEEE Sponsored Conferences

Member of Technical Coordinating Committee IEEE-MTT-5, "Microwave High Power Techniques"

Member of Speaker's Bureau of IEEE-MTT- 5

FACULTY TEAM MEMBERS

| NAME | ROLE/TOPIC | AWARDS /SPECIAL INFO |
|------------------|---|--|
| Dr Slim Boumaiza | Assistant Professor and iCORE Research Associate Research interests include multi-band and reconfigurable transmitters/receivers; advanced digital signal processing; design, characterization, modeling and linearization of high-power RF amplifiers | New academic staff member, joined the group from École Polytechnique Montreal in 2005. |

RESEARCH ASSOCIATES

| NAME | ROLE/TOPIC | AWARDS /SPECIAL INFO |
|------------------|--|---|
| Dr Anton Seregin | Narrow band interference cancellation in spread spectrum based receivers | Joined the iRadio Lab after five years experience with Hawawi of China. |
| Haykel Ben Nassr | Development of an embedded-system for digital predistorters | |

POSTDOCTORAL FELLOWS

| NAME | ROLE/TOPIC | AWARDS /SPECIAL INFO |
|-----------------|---|--|
| Dr Taijun Liu | Channel behaviour modeling and nonlinearity pre-compensation of wireless transmitters | Awarded a postdoctoral fellowship from FQRNT for 2006-2008. Co-supervised by Dr A. Sesay. |
| Dr Renato Negra | Power-efficient linear amplification in modern wireless transmitters | Recruited from the Swiss Federal Institute of Technology Zurich in January 2006. |

| PhD CANDIDATES | | |
|-------------------|---|--|
| NAME | ROLE/TOPIC | AWARDS /SPECIAL INFO |
| Oualid Hammi | Software defined multi-branch transmitters for wireless and satellite communication systems | NSERC Canada Graduate Scholarship (CGS-D), iCORE scholarship, and Dean's Research Excellence Award |
| Han Gil Bae | Linear and high efficient transmitter for WiMAX base stations | Joined the iRadio Lab. after 4 years experience in RFIC design with Samsung Electronics, Korea. |
| Mohamed Helaoui | Modified LINC transmitters for OFDM radios | Received the Dean's Entrance Scholarship |
| Bogdan Georgescu | Q enhancement of RFIC inductances | Co-supervised by Dr I. Finvers, Dept. of Electrical and Computer Engineering, University of Calgary. NSERC Post Graduate Scholarship (PGS-D), iCORE scholarship, TRILabs scholarship |
| Louay Degachi | Nonlinear large signal modeling of HBT transistors | Associate, École Polytechnique Montreal |
| Mohamad Mostageer | OFDM/LINC transmitters design | Associate, École Polytechnique Montreal Currently holding an International Graduate Scholarship from the Egyptian Government. |
| Sonia Bouajina | Behavioural modeling of RF power amplifiers with memory effects | Associate, École Nationale d'Ingénieurs de Tunis. Co-supervised by Dr M. Jaidane |
| Rim Barrak | Multi-standard receivers using RF sub-sampling technique | Associate École Supérieure des Communications de Tunis, Tunisia Co-supervised by Dr A. Ghazel |
| Taijun Liu | Dynamic behaviour modeling and nonlinearity pre-compensation for broadband transmitters | Associate, École Polytechnique Montreal Currently a postdoctoral fellow at the iRadio Lab. |



Dr Fadhel Ghannouchi and
Mohamed Helaoui



| MSc CANDIDATES | | |
|----------------------------|--|---|
| NAME | ROLE/TOPIC | AWARDS /SPECIAL INFO |
| Tony Pellerin | Design of integrated HBT based Doherty amplifier for satellite applications | Associate, École Polytechnique Montreal Co-supervised by G. Brassard, Canadian Space Agency. Currently holds a Digital Communication Engineer position, Canadian Space Agency. |
| Jérôme Sirois | Design and linearization of a Doherty amplifier for wireless and satellite communications | Associate, École Polytechnique Montreal Co-supervised by G. Brassard, Canadian Space Agency. NSERC Post Graduate Scholarship (PGS-M) and Canadian Space Agency Scholarship Currently with Freescale Semiconductor, Tempe, AZ, USA. |
| Li Jing | Implementation of digital base band predistortion | Associate, École Polytechnique Montreal Currently working at Nanowave Inc., Toronto. |
| Yang Tian | Design of LINC amplifier for CDMA communication. | Associate, École Polytechnique Montreal |
| Vijayachandran Ramchandran | Linearization of RF power amplifiers using digital RF predistortion technique | |
| Demirel Nejda | Sigma-delta based transmitters Visiting international student from Université de Bordeaux, France | Joined the iRadio Lab in February 2006. Co-supervised by Dr E. Kerhervé from the Université de Bordeaux, France. |

| OTHER TEAM MEMBERS | | |
|---------------------------|--|----------------------|
| NAME | ROLE/TOPIC | AWARDS /SPECIAL INFO |
| Christopher Simon | Technical support Provides technical support to students for PCB fabrication and instrumentation. | |
| Andrea Berbic | Administrative support | |

GRADUATES

| STUDENT | DEGREE/RESEARCH TOPIC |
|-----------|---|
| T. Liu | Dynamic Behaviour Modeling and Nonlinearity Pre-Compensation for Broadband Transmitters |
| J. Sirois | Design and Linearization of a Doherty Amplifier for Wireless and Satellite Communications |
| L. Jing | Implementation of Digital Base Band Predistortion |

COLLABORATIONS

| PARTICIPANTS | NATURE OF COLLABORATION |
|---|--|
| NATIONAL | |
| École Polytechnique Montréal, Dr M. Sawan Dr K. Wu | <p>Collaboration with Dr M. Sawan on digital implementation of the predistortion technique recently led to the approval of an US patent on the developed technology.</p> <p>Collaboration with the Poly-Grames Research Center (Dr K. Wu) concerns the access to advanced PCB fabrication facilities by iRadio team. In addition, two PhD students and one master candidate from École Polytechnique Montréal are currently supervised by Dr Ghannouchi. (Lead contact person: Dr Ghannouchi)</p> |
| Université de Québec, Dr A. Kouki | The ongoing themes of collaboration are related to HBT modeling and LINC-based amplifiers. Several joint papers have been co-authored with Dr Kouki's group. (Lead contact person: Dr Ghannouchi) |
| INTERNATIONAL | |
| Pohang University of Science and Technology (POSTECH), Korea Dr B. Kim | The main objective of this collaboration, started in 2005 is the testing and evaluation of the DPD linearization technology developed at the iRadio Lab on a high-power base station Doherty power amplifier (300 Watts) provided by POSTECH. (Lead contact person: Dr Ghannouchi) |
| Université de Tunis, Tunisia Dr A. Ghazel and Dr M. Jaidane | The ongoing themes of collaboration are related to behaviour modeling of nonlinear systems, implementation of DPD technology using DSP/FPGA modules and the design of multi-standard receivers using RF sub-sampling techniques. Several joint papers have been published that report the results obtained so far. Dr Ghannouchi is co-supervising the work of two PhD candidates. (Lead contact person: Dr Ghannouchi) |
| Université de Bordeaux, France. Dr E. Kerhervé | Collaboration was initiated this year with IXL laboratory of the Université de Bordeaux to study, analysis and assess the suitability sigma-delta based modulators in designing RF digital amplifiers. |
| INDUSTRIAL | |
| TRLabs, Canada Dr J. McRory | Initial discussions have been started with TRLabs about the design of highly efficient high-power amplifiers for wireless applications. Three PhD students, who are partially supported by TRLabs. (Lead contact person: Dr Ghannouchi) |
| Canadian Space Agency, Mr G. Brassard, Manager Digital and Power Electronics | The ongoing collaboration involves two research projects: the first one is related to the development of a large signal model of hetero-junction bipolar transistors (HBTs) supported by Fonds de Recherches sur la Nature et la technologies du Quebec (NATEQ); and, the second is related to the development of highly efficient Doherty power amplifiers for a S band micro-satellite transponder (Quick Sat program). A NSERC Collaborative Research and Development Grant (CRD) proposal, sponsored mainly by CSA, Focus Microwaves and Nanowave Technologies, to further study, investigate and design digital multi-branch Doherty amplification systems, was recently submitted to NSERC. (Lead contact person: Dr Ghannouchi) |
| Mitec Telecom, Canada Mr Iwan Jemczyk | Dr Ghannouchi has been collaborating with Mitec since 1998. The ongoing collaboration involves an NSERC strategic research project related to the development of DPD and LINC based amplifiers for 3G wireless base station amplifiers. (Lead contact person: Dr Ghannouchi) |
| Agilent Technologies, USA Mr A. Amini | This collaboration was triggered by one of our publications that reported on RF/DSP techniques for the improvement of the power-added efficiency of OFDM based transmitters, was initiated with Agilent Technologies last year. Privileged access to an Agilent software module (WiMAX library) was granted to the iRadio Lab to be used in RF/DSP simulation and design optimization of WiMAX transmitters. (Lead contact person: Dr Boumaiza) |
| Rockwell Collins, Government Systems, USA Dr G. Hegazi | Collaboration was initiated last year with Rockwell Collins, Government Systems, triggered by a publication that reported on the development of digital predistortion (DPD) scheme. System level analysis of Rockwell's transmitter has been carried out, and initial recommendations have also been communicated to them in a formal confidential technical report. Based on that, a research contract has been awarded. (Lead contact person: Dr Ghannouchi) |
| RFHIC Corporation, Korea | RFHIC, Korea has agreed to give the iRadio Lab research team access to their new GaN transistors, in order to support the research work. The iRadio Lab team will benefit from this privileged access to RFHIC foundries by being the leaders in the research and development activities related to the characterization and modeling of GaN transistors and their application to the design of wideband transmitters. (Lead contact person: Dr Boumaiza) |



INTELLECTUAL PROPERTY

| PATENT | | |
|---|---|---|
| PATENT/AUTHOR | TITLE/NAME | STATUS |
| Patent No. 7,035,345 E. Jecklen, F. M. Ghannouchi, M. Sawan, and F. Beaugard | Adaptive Predistortion Device and Method Using Digital Receiver | Approved in December 2005, US |
| INVENTION | | |
| AUTHOR | TITLE/NAME | STATUS |
| T. Liu, S. Boumaiza, and F. M. Ghannouchi | LBG Nonlinear Behavioural Model for Characterizing and Pre-compensating Broadband Communication Systems | Disclosure filed with UTI and patent will be possibly sought shortly. |

FUNDING

Dr Fadhel Ghannouchi has an iCORE Chair worth over \$1.5M over five years. His combined grants from CFI and NSERC give him \$512K and he holds a Tier 1 Canada Research Chair which contributes \$200K a year to his research program. Funding from industry includes \$429K as cash and in-kind contributions.



PUBLICATIONS

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M. Helaoui, S. Boumaiza, A. Ghazel and F. M. Ghannouchi, "Power and Efficiency Enhancement of 3G Multi-carrier Amplifiers Using Digital Signal Processing with Experimental Validation", *IEEE Trans. Microwave Theory and Tech.*, in press.

T. Liu, S. Boumaiza and F. M. Ghannouchi, "Augmented Hammerstein Predistorter for Linearization of Broadband Wireless Transmitters", *IEEE Trans. Microwave Theory and Tech.*, in press.

L. Degachi and F. M. Ghannouchi, "Systematic and Rigorous Extraction Method of HBT Small-Signal Model Parameters", *IEEE Trans. Microwave Theory and Tech.*, Vol. 54, Issue: 2, February 2006, pp. 682-688.

A. Issaoun, A. B. Kouki and F. M. Ghannouchi, "An Accurate and Compact Large Signal Model for III-V HBT Devices", *Solid-State Electronics Journal*, Vol. 49, Issue: 12, December 2005, pp. 1909-1916.

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D. Dousset, A. Issaoun, A. B. Kouki and F. M. Ghannouchi, "Wideband Close-Form Expressions for Direct Extraction of HBT Small-signal Model Parameters for all amplifiers bias Classes", *IEEE Proc. Circuits, Devices & Systems*, Vol. 152, Issue: 5, October 2005, pp. 441-450.

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M. Helaoui, S. Boumaiza, A. Ghazel and F. M. Ghannouchi, "On the RF/DSP Design-for-Efficiency of OFDM Transmitters", *IEEE Trans. Microwave Theory and Tech.*, Vol. 53, Issue: 7, July 2005, pp. 2355-2361.

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C. Larose and F. M. Ghannouchi, "Optimal Adaptation Methods and Class of Operation: Keys to Improving Feedforward Amplifier Power Efficiency", *IEEE Trans. on Vehicular Technology*, Vol. 54, Issue: 2, 2005, pp. 456-467.

REFEREED CONFERENCE PROCEEDINGS

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T. Liu, S. Boumaiza and F. Ghannouchi, "Identification and Pre-compensation of the Electrical Memory Effects in Wireless Transceivers", *2006 Radio & Wireless Symposium*, San Diego, USA, January 2006, pp. 535-538.

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F. M. Ghannouchi, "Advanced Radio Technology for 3G+ Communication Systems", Presentation in Chongqing University of Posts and Telecommunications (3G Research Center), Chongqing, China, 20 December 2005, Invited.

F. M. Ghannouchi, "Linearization Technology for 3G Power Amplifiers", Presentation in Great Communication Technology Co., LTD., Nanjing, China, 15 December 2005, Invited.

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