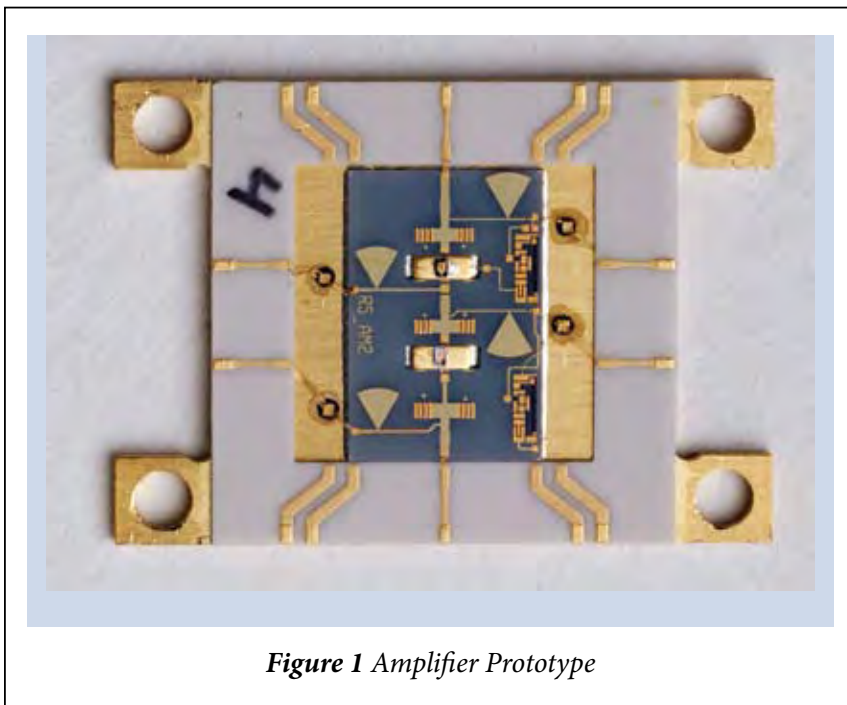


Intelligent RF Radio Technology



The Intelligent RF Radio Laboratory (iRadio Lab) mission is to develop new knowledge and innovative enabling technologies pertinent to intelligent radio systems and related applications that are valuable to partners and sponsors, and to train highly qualified personnel in radio frequency (RF) and wireless communications science and technology.



This laboratory is devoted to advanced research and development activities in intelligent RF radio technology applicable to broadband wireless communication systems. The research program is concerned with RF and microwave devices, circuits and systems; adaptive digital signal processing (DSP); modeling of devices, systems and channels; lin-

earization and equalization concepts; and multiple-input multiple-output (MIMO) systems; software-hardware implementation and integration issues; and, other related applications.

The iRadio Lab was formally launched on November 28th, 2005 and is already staffed with more than

fifteen 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 the Engineering building, allocated for printed circuit board fabrication and circuit prototyping, is under renovation. The iRadio Lab facilities are supported by a number of CAD based software tools, test benches and rapid prototyping setups.

This laboratory is positioned at the crossroads of several fields relevant to highly promising broadband wireless communication systems; it is in a position to provide a unique platform for pre-competitive research and for industrial and technological development.

Leading-edge research, development, testing, validation, and evaluation of new concepts and architectures relevant to software-defined and software-enabled RF radio activities are being conducted in collaboration with the RF and wireless communications

industries and government research and development (R&D) agencies. Despite its recent creation, the iRadio Lab has succeeded in the initiation of close formal collaborations with several national and international academic institutions, industry partners and government agencies. Several non-disclosure agreements to access proprietary information and/or technologies have been signed to support these collaborations. Furthermore, the iRadio Lab was formally accepted in February 2007 as an Associate Member of a European Center of Excellence (TARGET – Top Amplifier Research Groups in a European Team).

The innovative and applications-oriented R&D activities being carried out at the iRadio Lab have led to more than forty refereed journal and conference papers, a United States (US) patent and a provisional patent application. Four distinguished speakers have given talks to students and researchers at the University of Calgary (U of C) and a two-day course related to switching mode amplifiers was organized by the iRadio Lab which attracted engineers and researchers from the university and the local industry.

Research Program Overview

The Research Team

The people affiliated with the iRadio Lab encompass faculty members, research staff, students, support staff and associated members. The iRadio Lab personnel connected directly with the U of C include two faculty members, one technical support staff and one administrative support staff, a lab manager, three postdoctoral fellows, and twenty graduate students.

Research Partners

This laboratory is mainly funded by joint sponsorship from iCORE, Canada Research Council (CRC), Canada Foundation for Innovation (CFI) and the National Sciences and Engineering Research Council of Canada (NSERC). Formal academic collaborations are maintained with Canadian and international universities in the area of power amplifiers, and transmitters design and optimization. In addition, close collaborations have been made with major national and international leading companies, in the following areas: (i) semi-conductor technology (Freescale,

Nitronex, RFHIC); (ii) wireless and satellite communications infrastructure (Nortel Networks, Nanowave Technologies, Canadian Space Agency, Powerwave Technologies, Rockwell Collins); and, (iii) digital electronics, DSP and computer aided design software (Analog Devices, Altera, and Agilent Technologies).

Major Research Directions

The scope of this iCORE Professorship/CRC chair research program is related to the development of intelligent RF radio systems for emerging wireless and satellite communications. The main goal is the development of software-defined high-performance transceivers. This multidisciplinary research program calls for



broad knowledge in the fields of DSP and mixed signal technology, RF and microwave technology, and communications systems, including the implementation and manufacturing processes in these respective fields.

The ongoing research activities span over the following research directions:

Device, system, and channel modeling:

The development of device, circuit and system models is essential for the design and optimization of the RF front-end. Behaviour/channel modeling is a key element for system level analysis of radio systems as well as in pre-distortion and pre-equalization applications.

Design of power-efficient power amplifier modules:

The power amplifier (PA) is the most critical and expensive subsystem in all wireless systems, as its performance dictates the overall performance of the transmitter in terms of linearity and power efficiency. Accordingly, the development of power-efficient PA modules used in advanced transceiver architecture is essential for any high-performance transceiver design in hybrid and/or integrated technologies.

Signal processing techniques for wireless radio systems:

The advances in transceiver architectures call for the RF/DSP co-design approach, in order to ensure the desired functionality and optimal system level performance. This includes impairment pre-compensation, architecture dependant signal processing and conditioning.

Multi-band, multi-mode and multi-antenna software-defined radio based transmitters:

The design of such multi-band, multi-mode transmitters is an important element for the development of truly software-defined radio (SDR) based transmitters for the infrastructure of ubiquitous networks. The use of multi-antenna radio architectures will further improve system performance, mainly in terms of capacity, coverage, and service availability.

Adaptive multi-band reconfigurable receivers:

This is the counterpart of the multi-band transmitter required for software-defined high-performance transceivers. New architectures that support multi-frequency, multi-standard applications will be investigated.

These projects all serve the intention of the original research proposal, which was aimed at the development and advancement of knowledge and know-how related to the design of intelligent and reconfigurable RF front-ends for multi-standard broadband communications systems.

Research Projects

The research program is being conducted along five major research tracks.

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

The main goals of this research project are related to the development of realistic characterization techniques and accurate device and behavioural models of active RF devices/circuits and systems.

During the last year, study and investigation of scientific and technical problems related to the characterization and modeling of amplifiers and transmitters have been carried out. This work led to the development of innovative and original characterization and modeling approaches, which are required to successfully design spectrum-efficient and/or power-efficient transmitters for third generation (3G) and beyond wireless applications. An integrated software tool, the Nonlinear Behaviour Modeling System (NBMS), was developed to be able to perform the modeling task seamlessly and efficiently in an academic or industrial environment. The NBMS allows for accurate modeling and correction of any impairments due to the hardware components. This software resulted in an invention disclosure to the university and is being considered for further improvement and possible commercialization.

At the device level, an accurate extraction technique for hetero-junction bipolar transistors (GaAs HBT)

that takes into account the current crowding and self-heating effects has been developed. Furthermore, a gallium nitride (GaN) based high electron mobility transistor (HEMT) nonlinear model was developed and used in designing switching mode class D power amplifiers for wireless applications.

Advanced Power Amplification Systems for 3G and Beyond Applications

This research project targets the design of advanced multi-branch power amplification architectures that will achieve high-power efficiency. This encompasses the development of innovative linearization techniques and the use of emerging semi-conductor technologies.

In the last year, the iRadio team successfully developed a radio frequency switched-mode amplifier prototype, using a GaN transistor, which showed excellent power efficiency (about 80%). Furthermore, the team has proposed a new mode multiplexing linear amplification with nonlinear components (MM-LINC) that shows outstanding linearity and efficiency enhancement (better than 300%), when compared to a traditional linear amplification system with nonlinear components (LINC) amplification scheme. The iRadio team has also begun the development of a potential all-digital radio transmitter, suitable for future communications infrastructure, which will integrate the switched-mode amplifier prototype and a sigma-delta modulator.

Handheld and mobile terminal performance sensitivity, in terms of signal integrity and power efficiency, as a result of power amplifier/transmitters (PA/Tx) load-mismatch effects, was extensively studied in the previous reporting period. Attributed to the antenna vicinity and temperature changes, the load mismatch was found to be critical; an adequate compensation scheme was proposed to avoid significant deterioration of the transmitter performance.

Advanced Adaptive Digital Signal Processing Algorithms for Wireless Transceivers

The objectives of this research project are to develop an advanced DSP algorithm at the transmitter and receiver sides. This will further improve the performance of the designed transceivers by providing the required and optimized driving signals synthesized in the DSP module of the anticipated innovative multi-branch transmitter architectures.

The advancement of digital base band pre-distortion was an important research theme for the group last year. In particular, excellent power leakage in the adjacent channels and superior error vector magnitude performance were successfully obtained as a result of the linearization of wideband and nonlinear radio frequency transmitters. Critical issues, related to the use of digital base band pre-distortion techniques to linearize highly

nonlinear power amplifiers, were studied, and advanced pre-distortion techniques have been proposed and the optimization of the digital pre-distortion implementation in a hybrid DSP/FPGA platform was addressed. The application of recursive and iterative adaptive filtering techniques for the synthesis of the digital base band pre-distortion function allowed for substantial computation complexity reduction. Furthermore, an advanced blind signal peak-to-average power ratio reduction method has been applied to OFDM signals to further improve the power efficiency of the transmitter.

The direct conversion technique, which is found to be the most



Doctor S. Bensmida (left) and Professor F. Ghannouchi (right)

adequate for the software-enabled radios, suffers substantially from its relatively limited performance as a result of its inherent and unavoidable implementation imperfections (gain and phase imbalance, DC offset). In the reported period, the iRadio team successfully developed an adaptive algorithm that is able to detect and compensate for the impairments of direct conversion based WiMax transceivers.

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

This research project focuses on the development of SDR-based transmitters that will efficiently handle multi-standards. In addition, these transmitters have to be designed to offer concurrent operation with minimum hardware overhead. In order to achieve higher data throughput, multi-antenna architectures are being considered as a valuable solution.

The first phase of this research theme was aimed at the development of multi-band filters and power combiners using planar circuits. The iRadio team successfully built a dual-band band-pass filter to be used in dual mode WiMax/WCDMA transceivers. Furthermore, compact and high-performance multi-band power combiners were successfully built and will be used in the future in the development of a multi-band WiMax/WCDMA transceiver. Preliminary results relevant to the design of multi-band power amplifiers have been achieved.

In addition, multiple-input multiple-output (MIMO) based radio systems require multiplication of the number of RF front-ends used, in order to improve system performance. This comes at the price of higher hardware cost and complexity, as well as supplementary signal processing computation. A new adaptive antenna selection algorithm was developed as an efficient way to reduce the cost and complexity of these systems without compromising much of the performance of the radio link.

Adaptive and Tunable Receivers

The main objective of this research project is to design and prototype adaptive multi-band receivers to be used with the multi-band transmitters reported in the previous section.

In the last year, advanced multi-standard receiver architecture that can support UMTS, GSM, and IEEE 802.11 standards concurrently was developed using the RF sub-sampling technique. This original SDR-based receiver architecture was implemented in advanced design system (ADS) software. Further validation, using a rapid system level prototyping system, is planned for the near future.

Objectives for Next Year

Modeling

At the system level, the iRadio team plans to continue to work in the behaviour modeling area with more emphasis on developing new models that can be easily identified and implemented in commercial and widely available DSP and FPGA modules. Further improvement of the first release of the nonlinear behaviour model software will be carried out, in order to develop a trial version for marketing purpose and potential commercial use. Attempts to use a vector quantization approach to develop a table based robust behaviour model will be initiated this year. In addition, this approach has to provide the reverse model that can be used to compensate for linear and nonlinear impairments in the power amplifier or transmitters.

At the device level, efforts will be deployed to develop a nonlinear model for GaN HEMT that can be used in designing RF power amplifiers for wireless and satellite communication applications. The team is also planning to study GaN devices that will be provided to us by Nitronex Corporation, Cree Incorporated and RFHIC.

Power Amplifiers

Major suppliers of power amplifier/transmitter (PA/Tx) modules have recently pointed out the load-mismatch effects on mobile terminals performance, in terms of signal integrity and power efficiency. Experimental validation of this phenomenon is planned for the next year and is anticipated to lead to a compensation scheme that can be implemented at the system level in order to avoid significant transmitters' performance deterioration under load-mismatch conditions.

To increase the power-added efficiency of RF PAs substantially recent industry directions suggest the move from continuously driven PAs to switched-mode PAs. Therefore, the team is planning to continue the work related to the design and prototyping of switching mode (class D, class E) and harmonically controlled (class F) PAs. Targeted applications of interest to industrial sponsors are UMTS, WiMax, satellite, and avionics. These power amplifiers will be used within delta-sigma and Doherty based transmitters.

LINC-based amplifiers perform badly, in terms of power-added efficiency, when driven with highly varying envelope signals, such as CDMA and OFDM. MM-LINC architecture has been proposed to improve the overall power efficiency of the amplification system. The goal for next year is to further investigate the manner in which MM-LINC amplifiers' efficiency can be improved in the context of multi-carrier signals while assuring standard compliant signal quality. An integrated engineering 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

As a continuation of efforts in the digital pre-distortion area, the iRadio team is pursuing the development of a robust and accurate digital RF pre-distortion technique that does not require the pre-knowledge/access to the base band signal. This technology can be used on RF amplifiers and repeaters driven by RF signals. The synthesis of the digital RF pre-distortion function necessitates more advanced and recursive adaptive algorithms for identification purposes of the pre-distortion function.

Crest factor reduction techniques have been proposed and used to "cut" the peaks in the signals without greatly affecting quality, in terms of spectral re-growth and error vector magnitude metrics. Effort will be dedicated to experimental validation of the already developed blind crest factor reduction approach for WiMAX applications.

SDR Transmitters

Multi-band SDR-based transmitters have to maintain the performance of the RF chain for all the frequencies/channels considered. 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, the team will continue to study and investigation of possible techniques that can be used to achieve the design of these multi-frequency RF front-end key components. Efforts will be spent on designing multi-band multi-harmonic matching circuits for switching mode or/and harmonically controlled PAs.

The study and investigation of the transmitter architecture that allows for the communication signal to be kept in a digital binary format as close as possible to the antenna will also be carried out. Delta-sigma modulator based transmitters have been proposed in the past for relatively low frequency applications. The intention is to push the frequency limit of these transmitters further so that they can be used at RF frequencies.

Outreach

Community outreach activities:

- iRadio lab is an associate member of TARGET consortium.
- Dr Ghannouchi is a member of the strategy committee of the TARGET consortium.
- Dr Ghannouchi gave a series of talks in China in December 2006.
- In March 2007, Dr Ghannouchi made a technical presentation to the executive officers and senior technical staff of Nanowave Technologies about advanced radio systems technologies for satellite and avionics applications.

Antenna selection techniques can be used to optimize the number of RF frond-ends in MIMO systems and minimize the overall cost of MIMO based communication systems. Efforts will be spent next year on the development of robust and computational bearable algorithms that can be implemented in commercial DSP/FPGA.

Adaptive and Tunable Receivers

For the same reasons mentioned in the previous section, SDR-based receivers require frequency agility and/or multi-band operation capability. The study and investigation of multi-band RF filters and matching

circuits will be carried out next year for the purpose of designing a multi-band RF receiver head for dual applications.

In addition, further co-simulation and analysis of the developed tri-band (GSM, UMTS and WiFi) RF sub-sampling receiver architecture will be performed to evaluate its suitability in a real traffic environment, where the three communications signals can co-exist simultaneously. An experimental validation of this new multi-band receiver will be conducted using a quick prototype platform that uses both FPGA and DSP modules, as well as suitable analog-to-digital converters (ADCs) and accessory circuits.

Research Team Members and Contributions

<i>Team Leader</i>	
Professor Fadhel Ghannouchi	
Team Leader, Director of iRadio Laboratory, 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 and multi-band radio systems	
Member of College of Reviewers of Canada Research Chairs	
Session chair and workshop organizer in IEEE sponsored conferences	
Subcommittee / Track chair in IEEE sponsored conference (ICECS'2006, IMS'2007, RWS'2007, MWCAS/NEWCAS'2007, ISSSE'2007)	
Member of Technical Coordinating Committee IEEE-MTT-5, "Microwave High Power Techniques"	
Member of Speaker's Bureau of IEEE-MTT- 5	
IEEE Fellow (2007) for his contribution to advanced microwave amplification circuits and sub-systems	
Awarded the title of Guest Professor of Ningbo University, China	

<i>Research Associates</i>		
Name	Role/Topic	Awards/Special Info
Dr Anton Seregin	Narrow Band Interference Cancellation in Spread Spectrum Based Receivers	

<i>Faculty Team Members</i>		
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	Academic staff member IEEE Senior Member Officer of the IEEE Southern Alberta msection (secretary) IEEE COMMTTAP chapter chair Technical program chair of IEEE SIPS2006 conference

<i>PostDoctoral Fellows</i>		
Name	Role/Topic	Awards/Special Info
Dr Souheil Bensmida	Characterization of Microwave Circuits and Systems	Recruited from École Nationale Supérieure des Télécommunications, Paris, France in October 2006
Dr Taijun Liu	Channel Behaviour Modeling and Nonlinearity Pre-compensation of Wireless Transmitters	Awarded a postdoctoral fellowship from Le Fonds Québécois de la recherche sur la nature et les technologies (FQRNT) for 2006 - 2008 Co-supervised by Dr A. Sesay
Dr Renato Negra	Power-efficient Linear Amplification Systems for Modern Wireless Transmitters	Recruited from the Swiss Federal Institute of Technology Zurich in January 2006

<i>PhD Candidates</i>		
Name	Role/Topic	Awards/Special Info
Pouya Aflaki	RF Digital Predistortion Techniques	Received the Dean's entrance scholarship
Rim Barrak	Multi-standard Receivers Using RF Sub-sampling Technique	Associate, SupCom, Université Tunis Carthage, Tunisia Co-supervised by Dr A. Ghazel
Seyed Aidin Bassam	MIMO Transceivers for 4G Wireless Communication Systems	Received the Dean's entrance scholarship Co-supervised by Dr S. Boumaiza

<i>PhD Candidates Cont'd</i>		
Name	Role/Topic	Awards/Special Info
Sonia Bouajina	Behavioural Modeling of RF Power Amplifiers with Memory Effects	Associate, ENIT, Université Tunis El Manar; Tunisia Co-supervised by Dr M. Jaidane.
Louay Degachi	Nonlinear Large Signal Modeling of HBT Transistors	Associate, École Polytechnique Montreal
Walid Saber El-Deeb	Design of 4G Integrated Transceivers	Currently holding an international graduate scholarship from the Egyptian Government Co-supervised by Dr S. Boumaiza.
Bogdan Georgescu	Q Enhancement of RFIC Inductances	NSERC post graduate scholarship (PGS-D), iCORE scholarship, TRILabs scholarship Co-supervised by Dr I. Finvers
Oualid Hammi	Software Defined Multi-branch Transmitters for Wireless and Satellite Communication Systems	Currently holding the NSERC Canada graduate scholarship (CGS-D), and iCORE scholarship
Safar Hatami	Delta-sigma Modulator Based RF I/Q Transceiver for Software-Defined Radio	
Mohamed Helaoui	Modified LINC Transmitters for OFDM Radios	Received the iCORE international student award (September 2006 to August 2008) Co-supervised by Dr S. Boumaiza.
Mohamed Mostageer	OFDM/LINC Transmitters Design	Associate, École Polytechnique Montréal Currently holding an International Graduate Scholarship from the Egyptian Government

<i>MSc Candidates</i>		
Name	Role/Topic	Awards/Special Info
Han Gil Bae	Linear and Highly Efficient Transmitters for WiMAX Base Stations	Joined the iRadio Lab after 4 years experience in RFIC design with Samsung Electronics, Korea Co-supervised by Dr S. Boumaiza
Marie-Claude Fares	Effects of Nonlinear Distortions on Communication Systems	Supervised by Dr S. Boumaiza
Andrew Kwan	Implementation of Baseband Digital Predistortion Techniques	Co-supervised by Dr M. Smith

<i>MSc Candidates Cont'd</i>		
Name	Role/Topic	Awards/Special Info
Nizar Messaoudi	RF Power Amplifiers' Efficiency Enhancement Using Load Modulation Techniques	Supervised by Dr S. Boumaiza
Demirel Nejda	Visiting international student from Université de Bordeaux, France Sigma-delta Based Transmitters	Co-supervised by Dr E. Kerhervé
Tony Pellerin	Design of Integrated HBT Based Doherty Amplifier for Satellite Applications	Associate, École Polytechnique Montréal Co-supervised by G. Brassard, Canadian Space Agency
Vijayachandran Ramchandran	Linearization of RF Power Amplifiers using Digital RF Predistortion Technique	Co-supervised by Dr S. Boumaiza
Alexander Sadeve	Visiting international student from Université de Bordeaux, France Design of Multi-band Power Amplifiers	Co-supervised by Prof E. Kerhervé
Farzane Taringoo	Behavioural Modeling of a Dynamic Nonlinear System	Associate, École Polytechnique Montréal Co-supervised by Dr R. Malhame

<i>Other Team Members</i>		
Name	Role/Topic	Awards/Special Info
Andrea Berbic	Administrative support to Dr Ghannouchi and the iRadio Lab Team	
Oualid Hammi	Lab Manager	
Andrew Kwan	Undergraduate summer project	Undergraduate NSERC research scholarship from May 1, 2006 to August 31, 2006
Nizar Messaoudi	Undergraduate summer project	Undergraduate NSERC research scholarship from May 1, 2006 to August 31, 2006
Christopher Simon	Technical support PCB fabrication and instrumentation	

Visiting Speakers and Professors

Name	Role/Topic	Awards/Special Info
Dr Aly Fathy	Visiting Speaker, Reconfigurable Antennas for Multi-band Wireless Services	Seminar, July 5, 2006 Professor, University of Tennessee, Knoxville, USA
Mr. Nathan Sokal	Visiting Speaker, RF Power Amplifiers, Class A through S – How they operate, and when to use each	Two-day course, November 6 and 7, 2006 CEO and founder of Design Automation Inc., USA
Dr Ke Wu	Visiting Speaker, Unified and Accurate CAD Model for RF, Microwave and Millimeterwave Integrated Circuits and Antennas	Seminar, July 6, 2006 Professor, École Polytechnique, Montréal, Canada
Dr Toshiyuki Yakabe	Visiting Speaker, An Alternative Vector Network Analyzer Based on Six-port Technology	Seminar, June 9, 2006 University of Electro- Telecommunications, Tokyo
Dr Nadir Zia	Visiting Professor, Polar Transmitters Design	Invited Professor from Sultan Qaboos University, Oman



GRADUATES

<i>Name</i>	<i>Research Topic</i>	<i>Current Position</i>
PostDoctoral Graduates		
Dr Taijun Liu	Channel Behaviour Modeling and Nonlinearity Pre-compensation of Wireless Transmitters	Assistant Professor at the Ningbo University of China, China
PhD Graduates		
Rim Barrak	Multi-standard Receivers Using RF Sub-sampling Technique	Associate Professor, University of Tunis, Tunisia
MSc Graduates		
Demirel Nejda	Sigma-delta Based Transmitters	PhD candidate, Université de Bordeaux, France
Tony Pellerin	Design of a Doherty Tx for Micro-Satellite in HBT	Digital Communication Engineer, Canadian Space Agency
Research Associate		
Dr Anton Seregin	Narrow band interference cancellation in spread spectrum based receivers	

COLLABORATIONS

<i>Participants</i>	<i>Nature of Collaboration</i>
National Collaborations	
École Polytechnique Montréal Dr M. Sawan Dr R. Malhame	Collaboration with Dr M. Sawan on digital implementation of the pre-distortion technique recently led to the approval of an US patent on the developed technology
École Polytechnique Montréal Dr K. Wu	The collaboration with Poly-Grames Research Center (Dr K. Wu) concerns the access to advanced PCB fabrication facilities by the iRadio Lab team. Three graduate students from École Polytechnique Montréal are currently supervised by Dr Ghannouchi (Lead contact person: Dr Ghannouchi)
Université de Québec Dr A. Kouki	The ongoing theme of collaboration is related to LINC-based amplifiers. One joint paper has been co-authored with Dr Kouki's group (Lead contact person: Dr Ghannouchi)

<i>Participants</i>	<i>Nature of Collaboration</i>
International Collaborations	
Pohang University of Science and Technology (POSTECH), Korea Dr B. Kim	Related to the performance improvement of a Doherty power amplifier designed by the POSTECH team using the linearization techniques developed at the iRadio Lab (Lead contact person: Dr Ghannouchi)
Université de Tunis, Tunisia Dr A. Ghazel Dr M. Jaidane	The ongoing themes 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	Initiated last year with IXL laboratory of the Université de Bordeaux to study, analyze, and assess the suitability sigma-delta based modulators in designing RF digital amplifiers. Two graduate students from the Université de Bordeaux spent two terms at the iRadio lab (Lead contact person: Dr Ghannouchi)
Industrial Collaborations	
TRLabs, Canada Dr R. Davis	Concerns the development of an antenna selection algorithm for MIMO systems and RF front-end design for MIMO radio systems (Lead contact person: Dr Ghannouchi)
Canadian Space Agency, Canada Mr. G. Brassard	In the frame of a NSERC Collaborative Research and Development Grant (CRD) (2007-2009), this collaboration aims at the development of GaN based innovative Doherty power amplifiers intended for CSA's quicksat program. The ongoing collaboration covered the co-supervision of a master thesis of a CSA engineer (Lead contact person: Dr Ghannouchi)
Focus Microwaves, Canada Dr C. Tsironis	Focus Microwaves is sponsoring the ongoing NSERC Collaborative Research and Development Grant (CRD) (2007-2009), and providing privileged technical support for activities related to the load-pull characterization of active devices (Lead contact person: Dr Ghannouchi)
Nanowave Technologies, Canada Dr A. Rahal	Collaborating with Nanowave Technologies since 2006 within a NSERC CRD project, the ongoing collaboration involves an NSERC strategic research project related to the development of GaN based switching mode amplifiers for satellite and avionic applications. (Lead contact person: Dr Ghannouchi)
Nortel Networks, Canada T. Dashin	Initiated this year, Nortel's technical staff assisted with the two-day course organized by the iRadio Lab. Recently, Nortel Networks supported an NSERC strategic grant application (Lead contact person: Dr Ghannouchi)
Agilent Technologies, USA A. Amini	This work concerns the co-simulation and optimization of WiMAX transmitters within Agilent's Advanced Design System (ADS) software. For this purpose, privileged access to Agilent's ADS WiMax library was granted to the iRadio Lab (Lead contact person: Dr Boumaiza)

<i>Participants</i>	<i>Nature of Collaboration</i>
Industrial Collaborations Con't	
Rockwell Collins, Government Systems, USA Dr G. Hegazi	A nine-month contract was awarded to the iRadio Lab. (Due to the confidential nature of the work, details of this project are not reported). Non-confidential parts of this work related to GaN devices modeling were reported in joint publications (Lead contact person: Dr Ghannouchi)
Powerwave Technologies, USA B. Vassilakis	Initiated this year, this collaboration is aimed at the modeling and linearization of Powerwave’s commercial power amplifiers, as well as amplifier prototypes to be used in their future base stations infrastructure (Lead contact person: Dr Ghannouchi)
Freescall, USA J. Wood	Freescall is providing LDMOS based devices and evaluation boards of their products to be used as devices under test for the ongoing research topic related to the design of high-efficiency power amplifiers (Lead contact person: Dr Boumaiza)
Nitronex Corporation, USA P. Rajagopal	Initiated this year, this collaboration covers the support of a NSERC strategic grant application, as well as privileged access to Nitronex’s GaN device technology (Lead contact person: Dr Ghannouchi)
RFHIC Corporation, Korea	RFHIC, Korea, provides the iRadio Lab with privileged access to their GaN transistor products for characterization, modeling and application to the design of wideband RF power amplifiers (Lead contact person: Dr Boumaiza)
Altera, USA	This collaboration provides the iRadio Lab with FPGA boards within their university program (Lead contact person: Dr Boumaiza)
Analog Devices, USA	This collaboration provides the iRadio Lab with DSP boards and circuits within their university program (Lead contact person: Dr Ghannouchi)

INTELLECTUAL PROPERTY

<i>Patents</i>	<i>Title/Name</i>	<i>Status</i>
Applied for through UTI	LBG Behaviour Model	Applied for this year
US patent # 7,035,345, April 2006.	“Adaptive Predistortion Device and Method Using Digital Receiver”	Granted this year

FUNDING

Dr Fadhel Ghannouchi has a five year iCORE Professor award (\$1.5M). This year he received grants from CFI and NSERC (\$443K). He also holds a Tier 1 Canada Research Chair (\$200K). Other yearly funding comes from cash and contributions from industry (\$517K) and from the University of Calgary (\$694K).



PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

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O. Hammi, S. Boumaiza and F. M. Ghannouchi, "On the Robustness of Digital Predistortion Function Synthesis and Average Power Tracking for Highly Nonlinear Power Amplifiers", *IEEE Trans. Microwave Theory and Tech.*, in press..

M. Abd Elaal and F. M. Ghannouchi, "Modified LINC Architecture for OFDM-Based Communication Transceivers", *International Journal of Microwave and Optical Technology*, in press.

M. Helaoui, S. Boumaiza, F. M. Ghannouchi, A. B. Kouki and A. Ghazel, "A New Mode-Multiplexing LINC Architecture to Boost the Efficiency of WiMAX Up-Link Transmitters", *IEEE Trans. Microwave Theory and Tech.*, Vol. 55, Issue: 2, Feb. 2007, pp. 248-253.

S. Bousnina, L. Degachi and F. M. Ghannouchi, "Systematic Extraction Method for the Determination of HBT Temperature-Dependant DC Model Parameters", *International Journal of Microwave and Optical Technology*, Vol. 2, Issue: 1, January 2007, pp. 28-34.

L. Degachi and F. M. Ghannouchi, "Simple Technique for a Quick Evaluation of HBT Temperature-Dependant DC Model Parameters in Forward Active Regime", *International Journal of Microwave and Optical Technology*, Vol. 2, Issue: 1, January 2007, pp. 14-17.

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