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1. EXECUTIVE SUMMARY

The trends in communication networks are toward ubiquitous, distributed and cooperative networks, which will also be required to support the large demand for mobility and high-throughput specifications within the environment of multi-standard communications. This adds up to severe linearity requirements for wireless and satellite communications' mobile and fixed terminals, accompanied, in most cases, by high DC power consumption, resulting in very low power efficiency. Accordingly, future radio systems will need to be designed to meet all the aforementioned critical capabilities, as well as to be less energy hungry and more environmental friendly ("green"). The mission of the Intelligent RF Radio Laboratory (iRadio Lab) is the development of new knowledge and innovative enabling technologies pertinent to intelligent and green radio systems and related applications that are valuable to our 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 (R&D) activities relevant to intelligent and green RF radio technologies applicable to broadband wireless and satellite communication systems. The research programs of iRadio Lab are concerned with RF and microwave devices, circuits and systems; adaptive digital signal processing (DSP); modeling of device and systems; linearization and hardware impairment compensation concepts; multiple-input multiple-output (MIMO) radio systems; software-hardware implementation and integration issues; and, other related applications.

iRadio Lab was founded in May 2005; and, it is already staffed with more than twenty graduate students and talented researchers, recruited worldwide. The main space dedicated to iRadio Lab in the University of Calgary's ICT building (ICT 302) is being used as offices for graduate students and research staff, as well as the main instrumentation, simulation and design area. An auxiliary space in A Block of the Engineering building (ENA 5), used for printed circuit boards fabrication and circuit prototyping, was recently completed; and, the development of the fabrication process is completed and being used by graduate students and researchers. The iRadio Lab facilities are supported by a number of computer aided design (CAD) based software tools, test benches and rapid prototyping setups.

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 R&D agencies.

iRadio Lab has succeeded in the initiation of close formal collaborations with several national and international academic institutions, industry partners and government agencies. Ten non-disclosure agreements to access proprietary information and/or technologies have been signed to support these collaborations.

The innovative and applications-oriented R&D activities being carried out at iRadio Lab have led to more than forty refereed journal and conference papers, a Patent Cooperation Treaty (PCT) patent application, two US patent applications and one provisional US patent application. Four distinguished speakers were invited to give public talks at the University of Calgary. A team of six graduate students from iRadio Lab won first prize in the Software Defined Radio Challenge 2008, an international competition, which is organized yearly by the SDR Forum, that took place in Washington in October 2008. The iRadio Lab team was the only Canadian, and indeed the only non-US team, among the six competing teams.

During its fourth year, iRadio Lab was successful in securing substantial funding: $250K from the Natural Sciences and Engineering Research Council of Canada (NSERC), $63K from TRLabs, and $75K from industry. These monies supplement the $300K, $200K, and $120K yearly averages provided by iCORE, the Canada Research Chairs (CRC) Program and the University of Calgary, respectively, over a 5-year period. In addition, in-kind contributions and equipment donations and loans in the amount of about $270K from industrial partners and $100K of in-kind contributions from the University of Calgary have been obtained during the reporting period.

2. RESEARCH PROGRAM OVERVIEW

The Research Team

There are many people affiliated with iRadio Lab, they include faculty members, research staff, students, support staff, visiting and adjunct researchers and industry collaborators. The head count of the iRadio Lab personnel affiliated directly with the University of Calgary currently includes one faculty member, one technical support staff, one administrative support staff, one lab manager, two research assistants, two postdoctoral fellows, one visiting scholar, and sixteen graduate students.

Research Partners

This laboratory has been mainly funded by joint sponsorship from iCORE, CRC, NSERC and the Canada Foundation for Innovation (CFI). Formal academic collaborations are maintained with Canadian and international universities in the area of device and system level modeling, power amplifier design and optimization, and software defined radio (SDR) based transceivers. In addition, close collaborations have been made with major leading national and international companies and agencies in the following areas:

i. semi-conductor technology (Freescale Semiconductor, Nitronex, RFHIC, Cree);

ii. wireless and satellite communications infrastructure (Nortel, Nanowave Technologies, the Canadian Space Agency, Powerwave Technologies, NXP);

iii. digital electronics, digital signal processing (DSP) and CAD software (Analog Devices, Altera, Agilent Technologies, Lyrtech, Canadian Microelectronic Corporation).

Major Research Directions

The scope of this iCORE/CRC 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 and environmentally friendly transceivers. This multidisciplinary research 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 the respective fields.

The ongoing research activities span over the following research directions that were identified in the original research proposal.

Modeling Technology

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

Green RF Electronics

The power amplifier (PA) is the most critical and expensive subsystem in all RF 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

architectures is essential for any high-performance and environmentally friendly (green) transceiver design in hybrid and/or integrated technologies.

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

Software Defined Radio
The design of multi-band, multi-mode transmitters is an important element for the development of truly 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 and Reconfigurable Receivers
This is the counterpart of the multi-band transmitter required for software-defined high-performance transceivers. New architectures are considered critical for the development and deployment of multi-frequency, multi-standard communications systems.

All the activities already carried out by iRadio Lab, as well as those planned, are in line with the aforementioned research directions. These projects all serve the intention of the original research proposal (submitted to iCORE and CRC), 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 communication systems. The optimization of power-added efficiency, due mainly to the reduction of DC power consumption of RF radios, is one of the objectives of the research program as initially stated in the chair proposal; and, since it may favourably impact the environment, this research thrust is being branded as green RF electronics, to better reflect its importance to the nontechnical person and to society at large.

3. RESEARCH PROJECTS

The research program is being conducted along the aforementioned five major research tracks. The achievements related to each of these five projects are reported and evaluated, in light of the initial main goals relevant to this project.

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

The primary objectives of this research project cover the accurate characterization and modeling of RF and microwave active devices, circuits and systems.

Over the last year, the emerging gallium nitride (GaN) technology for power HEMT (high electron mobility transistor) transistors was the main focus of our research activities in the area of device characterization and modeling. This technology is expected to have great potential for future wireless communications infrastructure by achieving wideband operation with very high power efficiency and acceptable linearity performance. Nonlinear models dedicated to switching-mode power amplifier (SMPA) design have been developed. A straightforward and time-efficient design methodology for SMPAs operating in class D, class E and class F was proposed using the switch based equivalent circuit model. In addition, an accurate nonlinear multidimensional table based model, constructed using DC and AC measurements data, was developed and has been implemented in ADS (Agilent Design Software). This model was found to be accurate enough to predict the performance of the transistor in the power back-off region as well as in the saturation region. An inverse class F power amplifier (PA) operating at 2.14 GHz was designed using this model, and there was good agreement between the actual measurement results and their counterparts obtained by simulation using the developed model. Experimental load-pull data based models are also being considered for the modeling of GaN transistors to be used in the design of continuously driven PAs. The activities carried out within this area have been performed in close collaboration with academic (ETS – École de Technologie Supérieure, Université du Québec) and industrial partners (Nortel and Nitronex).

At the system level, it has been found that the current metrics used for behavioural model performance assessment are not accurate enough, since they fail to effectively quantify a key component (memory effects) of the behaviour of the system being modeled. Consequently, and as a continuation of the work achieved last year on the extraction of the static nonlinearity in power amplifiers / transmitters exhibiting memory effects, an innovative approach for model validation was recently proposed. This includes new metrics and methods that can efficiently quantify the accuracy of the behavioural model in mimicking both the static nonlinearity and the memory effects exhibited by the device under test. Furthermore, this method, which is based on static nonlinearity post-compensation, requires only a single set of measurements, contrasting with all the previously reported approaches.

In addition, a new class of low computational complexity behavioural models for power amplifiers / transmitters exhibiting strong memory effects have been proposed. These models, namely the twin-nonlinear two-box models, lead to

better performances with up to a 50% reduction in the number of parameters when compared to the state-of-the-art behavioural models.

Wideband characterization of power amplifiers / transmitters was initiated this year. Various commercial test equipment were thoroughly evaluated, in order to come up with a potential test bench solution for an experimental setup that can be used for characterization application with an instantaneous bandwidth of more than 300 MHz. Preliminary results were obtained using the test equipment. Further validation will be carried out next year.

The activities carried out within this area have been performed in close collaboration with an industrial partner, Powerwave Technologies.

Within the ongoing NSERC collaborative research and development grant project supported by Canadian Space Agency dealing with the design of digitally driven multi-input Doherty PAs, initial results were obtained for individual characterization of the carrier and peaking amplifiers while they are operating within the Doherty load modulation mechanism. This offers a unique in-depth observation of the behaviour of Doherty amplifier. This characterization approach is being directly used for innovative behavioural modeling applications of Doherty PAs and will, ultimately, enable the prototyping of high-performance digitally driven Doherty PAs.

Green RF Power Amplification Systems

The objective of this research project is the design of advanced multi-branch power amplification architectures that will achieve high performances in terms of power efficiency, linearity and bandwidth, in order to be used with highly demanding applications, such as 3rd and 4th generation (3G and 4G) standards. This encompasses the development of innovative linearization techniques for advanced architectures and the use of emerging semiconductor technologies, in order to improve the power efficiency and linearity performances of such advanced transmitters.

In continuation of work done in previous years on the development of the highly efficient switching-mode amplifier design, the analysis and design methods were further advanced, in order to achieve even higher performances for different applications and a variety of standards. In particular, when targeting the design of class F and inverse class F PAs for 4G applications, new techniques to reduce the losses in the matching networks were developed, analyzed and validated. As a result, a state-of-the-art performance was obtained for an inverse class F design at 2.45 GHz. Using this optimization technique, the drain efficiency was significantly increased with the new design. In addition, a current mode class D was designed at 2.4 GHz for use in 4G applications and wireless transmitters with advanced balanced architectures, such as delta-sigma based transmitters. A

new approach was used in the design of the current mode class D, which resulted in improving the drain efficiency to reach the barrier of 70%.

The activities carried out within this area are supported through an NSERC strategic project grant and have been performed in close collaboration with industrial partners (Nitronex and Cree)

The optimization of Doherty PAs to improve their linearity and/or efficiency was thoroughly studied over the past year. This led to the design of an improved Doherty PA that has superior linearity performance. It was demonstrated experimentally that this linearity increased with a costless optimization of the RF circuit, but the power efficiency of the circuit was not affected. The linearization of the designed prototype using a digital predistortion technique led to the best trade-off in terms of linearity and efficiency that has been reported in the open literature for Doherty PAs driven by 20 MHz WCDMA (wideband code division multiple access) signals. Further optimization of the circuit is being considered. In particular, the effects of the output phase offset line on the load modulation seen by the carrier amplifier are being evaluated.

The designed PA prototypes were tested with new advanced transmitter architectures using an out phasing technique to improve the efficiency versus linearity trade-off in the power back-off region. Indeed, a reverse MM-LINC (mode-multiplexing linear amplification with nonlinear components) technique was proposed, simulated, implemented and tested for 3G applications. The measurement results showed that the proposed architecture is capable of achieving a good linearity versus efficiency trade-off without requiring high pre-processing computational complexity, in comparison to the most commonly used linearization techniques, mainly digital predistortion. This characteristic makes the proposed approach a good candidate for mobile and broadband applications.

A LINC amplification system with non-isolated combiner was also designed using highly efficient switching-mode PAs. The combining structure was optimized in order to improve efficiency in the power back-off region. The system was tested and validated with a 3G WCDMA signal. The measured combining efficiency was higher than 50% at a 6 dB back-off operating power level.

The activities carried out within this project are supported through an NSERC collaborative research development grant and have been performed in close collaboration with the Canadian Space Agency.

Advanced Adaptive Digital Signal Processing Algorithms for Wireless Transceivers

This research project targets the development of advanced adaptive signal processing techniques for performance improvement of wireless transceivers.

This can be divided into three tracks: nonlinearity compensation, impairment compensation and architecture dependant signal processing.

For nonlinearity compensation, several algorithms have been developed for base station and mobile terminal transmitters driven by WCDMA or/and WiMAX (Worldwide Interoperability for Microwave Access) signals. These algorithms are mainly related to the cancellation of memory effects exhibited by RF PAs / transmitters. Results obtained illustrate the ability of the developed approaches to improve the convergence behaviour of predistortion algorithms using behaviour or artificial neural networks based models. Critical issues related to the computational complexity of digital predistortion systems have been considered in the predistorter's identification and implementation steps.

Excellent linearization capabilities have been achieved for highly nonlinear Doherty transmitters over a 20 MHz modulation bandwidth. Moreover, the RF-digital predistortion platform was assembled and used to digitally linearize medium-power RF PAs. The implementation of memory compensation algorithm within the FPGA (field-programmable gate array) platform was completed and similar results were obtained when using commercial instruments, such as arbitrary waveform generators and vector spectrum analyzers.

A new algorithm to compensate for in-phase/quadrature (I/Q) imbalance in direct conversion transmitters that does not require any specific training sequence or the use of an ideal I/Q imbalance-free demodulator in the feedback loop was developed and validated.

Architecture dependant digital signal processing (DSP) is another area of investigation. Signal processing algorithms are being developed to provide the required and optimized driving signals synthesized in the DSP module of the considered innovative multi-branch transmitter architectures. This covers LINC architecture and its derivative, digital Doherty PAs, as well as delta-sigma based transmitters.

The activities carried out within this project are supported through an NSERC collaborative research development grant and have been performed in close collaboration with the Canadian Space Agency

Multi-Band, Multi-Mode and Multi-Antenna SDR-Based Transmitters

This research project mainly focuses on the development of software-defined radio (SDR) based transmitters that are able to handle multi-standards using the same hardware. The RF parts of the transmitters operate concurrently in multi-bands to fulfill the multi-standard requirements. In addition, the multi-antenna architectures are considered as efficient techniques to improve the data throughput and spectral efficiency of the transmitters. The baseband part of the

transmitter should be reconfigurable, in order to handle different standards using the same hardware.

In the context of a reconfigurable baseband transmitter platform, we proposed a new reconfigurable DSP platform, which can be applied to design a reconfigurable SDR baseband transmitter. By using a combined advanced processing technique, such as DSP, GPP (general purpose pre-processing) and FPGA, the platform can be reconfigured to different existing standards in seconds. In addition, with an elaborate user-hardware interface and communication protocols, upcoming standards and waveforms can be configured; and, the platform can be updated in less than 24 hours. The proposed platform was tested and validated with WLAN (wireless local area network) IEEE 802.11 waveforms. The concept and design was achieved in the context of an international student challenge and won first prize.

We continued the performance improvement of the delta-sigma based, all-digital, multi-standard radio transmitter platform developed and prototyped last year. We proposed a new delta-sigma implementation architecture that uses parallel processing to increase the processing speed of the platform using the same digital processing hardware as conventional architecture. Additional modifications and upgrading of the platform's hardware were necessary to adjust its functionality to the new delta-sigma architecture. The new architecture was implemented and validated on the delta-sigma platform and was shown to be capable of increasing fourfold the processing speed and, therefore, the signal bandwidth that can be handled by the platform.

We also continued the research study on the performance improvement of the multiple-input multiple-output (MIMO) transceivers. In this regard, the digital predistortion (DPD) linearization techniques have been extended to MIMO transmitter applications where unavoidable RF crosstalk affects degrade the performance of the linearization technique. It was shown that, in the presence of RF crosstalk, traditional DPD architecture is not an appropriate solution; therefore, a new digital predistortion technique (crossover digital predistorter) was developed, which simultaneously compensates for both the transmitter nonlinearity and the RF crosstalk in the MIMO transmitter. The promising feature of the crossover digital predistorter is its blind compensation of the RF crosstalk. The performance improvement of the proposed solution was studied and validated by measurements. Extension of the proposed topology to compensate for other sources of linear and nonlinear distortion at the transmitter, such as I/Q imbalance, is in progress. Furthermore, the possibility of adapting the proposed topology for multi-band applications is under investigation. This crossover DPD is being considered for protection through a patent filing.

The activities carried out within this project are supported through an NSERC strategic grant and iCORE funds and have been performed in close collaboration with Nortel.

Adaptive and Tuneable Receivers

Along with the multi-band transmitter project reported in the previous section, the design and prototyping of multi-band receivers continues to be carried out, as in previous years.

This project focuses on the development of multi-band and tuneable receivers. For this purpose, reconfigurable hardware is needed for the baseband processing block. In this context, similar to the reconfigurable transmitter developed in the multi-band SDR transmitter project, a reconfigurable baseband receiver was designed in an SDR reconfigurable platform. The receiver has the capability to be reconfigured to different existing standards in seconds and can be extended to new standards in a few hours. This was made possible with the elaborate signal processing architecture proposed for the developed SDR platform. The reconfigurable receiver was also tested and validated with a WLAN 802.11 waveform.

In addition, we worked on the development of new multi-band adaptive RF receiver for multi-standard applications. This new topology consists of de-interleaving and subsampling the RF signal, in order to digitize and directly acquire the baseband signal, as closely as possible, from the receiving antenna. Contrary to traditional direct down-conversion receivers, the proposed topology only needs a single branch to down-convert and extract the baseband information. Using a single-branch receiver eliminates the I/Q mismatch issue of traditional direct down-conversion receivers. The simplicity of the proposed receiver architecture makes it an alternative solution for multi-band and multi-standard applications. The receiver topology was proposed based on multiplying the RF signal with a single sine wave followed by a subsampling technique. The proposed architecture was validated with commercial off-the-shelf RF components: the measurement results proved the functionality of the architecture.

In the past year, an advanced multi-standard receiver architecture that can concurrently support Universal Mobile Telecommunications System (UMTS), Global System for Mobile communication (GSM) and WLAN standards was developed using subsampling techniques. The proposed multi-standard receivers consist of novel two-stage RF and intermediate frequency (IF) subsampling techniques to relax he complexity of IF filter design. This original SDR based receiver architecture was implemented in advanced design system (ADS) software based on realistic components. A very broadband (12 GHz) track-and-hold (T&H) circuit, which is a key component, needed for rapid experimental evaluation is being procured. This T&H circuit will be interfaced for a quick prototyping FPGA based platform, in order to automatically perform the experimental testing with three types of modulated signals (EDGE – Enhanced Data rates for GSM Evolution; CDMA – code division multiple access; and, WiMAX).

The activities carried out within this project are supported through an NSERC discovery grant and iCORE funds.

4. OBJECTIVES FOR NEXT YEAR

The objectives of the next year are in line with the research directions of the chair's original proposal. These objectives are subdivided according to the research tracks and projects identified in the overview of the research program.

Modeling Track

As a continuation of our efforts in the modeling area, a robust model validation technique will be developed. This technique will enable model comparison and performance assessment, in both frequency and time domains, using one performance assessment metric. In addition, wideband characterization of RF transmitters will be initiated. This is foreseen as a strategic path for the development of behavioural models and, consequently, nonlinearity compensation algorithms that will cover full RF bands. Commercial test equipment presently does not support such wide bandwidths; accordingly, custom measurement setups and techniques need to be developed. State-of-the-art behavioural models will be augmented to take into account additional nonlinearity sources triggered by the wideband drive signals. The behavioural modeling of the designed multi-band PAs driven by multi-standard signals will also be initiated.

At the transistor level, the study of GaN devices will be continued through intensive measurements and modeling activities in collaboration with LACIME Laboratory at ETS. Several devices provided by industrial partners who are developing GaN-based transistors, such as Cree, Nitonex and Eudyna Devices, have been procured. The main objective is the development of a full-fledged model of GaN transistors suitable for continuously driven, as well as switching-mode, PA design.

As a continuation of the current work being done on the modeling of Doherty PAs, the use of the recently proposed approach for the separate characterization of the carrier and peaking amplifier is expected to lead to innovative behavioural models suitable for Doherty PA. Furthermore, three-box behavioural models, as well as neural networks based two-box models, will be developed and evaluated for wideband applications.

Power Amplifiers Track

During the past year, we focused on the design of high-efficiency RF switching mode PAs for wireless communication applications with a carrier frequency in the range of 2-3 GHz. Matching network topologies were developed that optimized matching network architectures that reduced the power losses in the transmission lines. This results in efficiency improvement of the PA, in order to reach state-of-the-art performances. In the next period, we will focus on extending this knowledge to satellite and wireless personal area networks that work at millimetre wave (mm-wave) frequencies. Working at higher frequencies is expected to be challenging in terms of fabrication and implementation technologies, as well as device and physical phenomena limitations.

It is also anticipated that work will begin on the implementation of a multi-mode Doherty transmitter for wireless personal area network applications at mm-wave frequencies. Contrary to conventional transmitters, the multi-mode Doherty transmitter uses different modes of operation. The selected mode varies as a function of the instantaneous power of the input signal. The choice of the modes and their thresholds of operation will be studied and optimized, in order to improve the linearity and efficiency of Doherty amplifiers without requiring complex pre-processing algorithms. This is extremely useful for ultra-wideband applications and for low- and medium-power applications where the power consumption of the digital signal processors is not negligible in comparison to the RF section and where the implementation of digital predistortion techniques is not feasible. This multi-mode technique was tested with different amplification architecture – a LINC system – and was shown to be very effective in achieving a good trade-off between power efficiency and linearity without the need of excessive signal processing. Its use with a Doherty PA is expected to further improve the performance of the wireless transmitter.

DSP for Wireless Communications Track

Our recent research activities on digital predistortion (DPD) will be extended for both baseband and RF technologies. On the baseband side, 30 MHz of instantaneous correction bandwidth will be targeted as a first step and then broaden to up to 60 MHz. This activity will be carried out in conjunction with the wideband characterization of RF PA / transmitter systems. The implementation of the predistortion function will create several challenges, and the developed low complexity predistortion functions are expected to play an important role in enabling the implementation of the wideband DPD systems. The development of RF-digital predistortion systems that compensate for memory effects will be pursued over the next year. This will lead to the experimental validation and prototyping of RF-digital predistortion systems that are able to compensate for memory effects. This technology can be used on RF amplifiers and repeaters driven by RF signals where there is no access to a baseband signal.

The work on the linearization of PAs and transmitters under wideband (30 MHz and more) drive signals will be pursued. The main limitation observed so far is mainly due to the dynamic range of the observation path. Accordingly, a particular interest will be given to the dynamic range improvement in the experimental setup considered for the wideband characterization of PAs / transmitters. Furthermore, the effects of crest factor reduction (CFR) on the performance of DPD based linearizers will be investigated in depth. The objective is the determination of the origin of the linearization capabilities reduction, in order to be able to efficiently combine CFR techniques and DPD algorithms without any significant drawback on the system level performance.

One of the major challenges to achieving maximum performance from MIMO transceivers is the ability to maintain acceptable levels of impairments and nonlinearity that occur due to the unavoidable implementation imperfection in the MIMO chipset design process. In fact, having more than one transceiver on a single chipset introduces new sources of impairments, such as common local oscillator (LO) leakage and signal coupling between the different transceivers. Not only is the investigation of the validity in MIMO transceivers of the previously proposed compensation techniques for the single input, single output (SISO) transceiver in the presence of these new impairments important, the development of new techniques to compensate for these impediments is also essential. The extension to MIMO transceivers of the available DPD techniques for SISO transceivers, by taking into account the effects of crosstalk, will be also be investigated.

SDR Transmitters Track

The study and investigation of true digitally based transmitter architecture that allows for the communication signal to be kept in a digital binary format as close as possible to the antenna will be continued and intensified. In the past year, significant research efforts were expended on tackling the implementation issues in delta-sigma modulators for GHz ranges; however, the designed proof-of-concept prototype still needs further improvement at both the signal processing and hardware stages.

Implementation and validation of wider band delta-sigma modulators for GHz frequency applications was made possible with parallel processing topology and high-speed multiplexers. However, the performance obtained in terms of power efficiency was relatively low. In the last few months, a preliminary analysis and study were carried out to investigate the possibility of increasing the power efficiency of these transmitters while maintaining the all-digital characteristics of the delta-sigma based transmitters. We intend to study, design and test a new delta-sigma architecture based on multilevel quantization. The architecture was briefly investigated, and preliminary results showed its potential to achieve high efficiency. The implementation of this architecture will require a special design of the RF part, especially the PA. It is anticipated that some time will be allocated to

the design and optimization of a switching-mode PA suitable for multilevel quantization delta-sigma modulators

Adaptive and Tuneable Receivers Track

In addition to the work carried out on the design and implementation of a new interleaved subsampling receiver, a dual-band RF-digital predistortion system for linearized transmitter architecture in SDR applications is proposed. This dual-band linearizing system will incorporate a subsampling receiver for nonlinear characteristics identification of PAs. With a capability of wideband correction, RF-digital predistortion is a potential candidate for implementation of a wideband predistorter as a linearizer. Moreover, being nonparametric, RF-digital predistortion does not rely on any knowledge of the signal structure, coding and other modulation information and, hence, can be used for both multi-band and multi-mode applications. With judicious selection of the track-and-hold sampling frequency, the subsampling receivers will down-convert the two carriers with their respective nonlinearities (which are generated as adjacent channel leakages) within the first Nyquist zone without overlapping.

5. RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

Team Leader		
Name	**Role / Topic**	**Awards / Special Info**
Dr. Fadhel Ghannouchi	Team Leader, Director of iRadio Lab, iCORE Professor in Intelligent RF Radio Technology, 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.	Professor Ghannouchi selected as IEEE-MTT-S Distinguished Microwave Lecturer (DML) for the three year period 2009-2011. Dr. Ghannouchi was inducted as a Fellow of the Engineering Institute of Canada (March 09). Dr. Ghannouchi selected as a finalist for an ASTech award (October 08) Dr. Ghannouchi received the 2007 ECE

		department research excellence award (June 2008) Dr. Ghannouchi received the 2007 Schulich School of Engineering research excellence award (June 2008) Dr. Ghannouchi elevated to the Fellow grade of the Institution of Engineering and Technologies (IET, formally IEE) (September 2008) Session chair and workshop organizer of IEEE sponsored conferences (EuMC'2008, IMS'2009, RWS'2009. Subcommittee / track chair of IEEE sponsored conferences (ICECS'2008, RWS'2009) Member of the International Advisory Board of the Gigahertz Research Centre, Sweden (2007-present)

Visiting Professor / Researcher		
Name	**Role / Topic**	**Awards / Special Info**
Dr. Abbas Mohammadi (August 08-April 09)	Visiting Researcher Research interests: homodyne six-port	Professor at Amirkabir University of Technology, Iran

	receivers and MIMO radios	

Visiting Speakers		
Name	**Topic**	**Special Info**
Dr. K. Wu	Multi-port technique for RF and millimeter-wave software-defined radio (SDR) applications	Professor at École Polytechnique de Montréal
Dr. N. Boulejfen	Analytical prediction of spectral regrowth and correlated and uncorrelated distortion in multicarrier tireless Transmitters	Professor at University of Hail, Kingdom of Saudi Ararabi (KSA)
Dr. A. Mohammadi	Six-port based radio systems	Professor at Amirkabir University of Technology, Iran

Research Associates / Assistants		
Name	**Role / Topic**	**Awards / Special Info**
Farzaneh Taringou	Research Assistant Behavioural modeling of communication transceivers	
Peter Stacha	Technical Support Staff RF circuits modeling and fabrication	
Harish Pandey	Technical Support Staff Development of printed circuit board (PCB) laboratory	

Chen-Yu Hsieh	Research Assistant Delta-sigma modulator implementation on FPGA	
Meenakshi Rawat	Neural network modeling of radio systems	Worked as a scientist / engineer for four years in the Indian Space Research Organisation (ISRO), India

Postdoctoral Fellows		
Name	**Role / Topic**	**Awards / Special Info**
Dr. S.-C. Jung (April 2008 – July 2008)	Doherty power amplifiers	Awarded a PDF fellowship from the Korean Government
Dr. R. Negra (April 2008 – May 2008)	Switching-mode power amplifiers	
Dr. S. Bensmida (April 2008 – August 2008)	Characterization of RF transistors	
Dr. L. Degachi (April 2008 – October 2008)	Linear modeling of transistors	PDF at. Université de Québec
Dr. A. Jarndal (October 2008 – February 2009)	GaN transistor non-linear modeling	Associate with Université de Québec. Presently holds a faculty position at Hodeidah University, Yemen
Dr. N. Boulejfene (July-August 2008)	Nonlinear network modeling and analysis	Presently holds a faculty position at the University of Hail, KSA
Dr. Mohamed Helaoui	All-digital transmitter design	Effective January 1, 2009
Dr. Oualid Hammi	Behavioural modeling of communication systems	Effective January 1, 2009

Ph.D. Students		
Name	**Role / Topic**	**Awards / Special Info**
Oualid Hammi	Software defined multi-branch transmitters for wireless and satellite communication systems	Awarded an NSERC Canada graduate scholarship (CGS-D) and an iCORE scholarship Graduated in December 2008.

Mohamed Helaoui	Modified LINC transmitters for OFDM radios	Awarded an iCORE international student scholarship (September 2006 to August 2008) Graduated in December 2008.
Safar Hatami	Delta-sigma modulator based RF I/Q transceiver for software-defined radios	Awarded an iCORE international student scholarship (September 2006 to August 2008)
Seyed Aidin Bassam	MIMO transceivers for 4G wireless communication systems	Passed his candidacy exam, December 10, 2008
Pouya Aflaki	GaN Based PA design with application to polar transmitters	Passed his candidacy exam, December 11, 2008
Walid Saber El-Deeb	Design and implementation of RF waveform measurement system	Holds an international graduate scholarship from the Egyptian Government Passed his candidacy exam, November 20, 2008
Mohamed Mostageer	OFDM/LINC transmitter design	Associate, École Polytechnique de Montréal Currently holds an international graduate scholarship from the Egyptian Government
Sonia Bouajina	Behavioural modeling of RF power amplifiers with memory effects	Associate, École Nationale d'Ingenieurs de Tunis, Tunisia Co-supervised by Dr. M. Jaidane
Afef Hargel	Memory-Polynomial	Associate, Faculté des

	Based models for RF transmitters linearization	sciences, University of Tunis, Tunisia Co-supervised by Dr. A. Gharsallah
Mohammed Mojtaba Ebrahimi	Multi-band transceiver design	
Junjie Liu	Indoor GPS radio transceiver design	Currently holds an NSERC Canada graduate scholarship (CGS-D) and an iCORE scholarship

M.Sc. Candidates		
Name	**Role / Topic**	**Awards / Special Info**
Vijayachandran Ramchandran	Linearization of RF power amplifiers using digital RF predistortion technique	
Andrew Kwan	Implementation of baseband digital predistortion techniques on a DSP / FPGA platform	Co-supervised by Dr. M. Smith.
Meenakshi Rawat	Neural network modeling of radio systems	Joined iRadio Lab as student on September 2008
Karun Rawat	Implementing of RF/digital predistortion system with memory effects compensation	Worked as a scientist / engineer for four years in the Indian Space Research Organisation (ISRO), India
Farzaneh Taringou	Behavioral modeling of dynamic nonlinear systems	Associate, École Polytechnique de Montréal Co-supervised by Dr. R. Malhame Graduated in April 2008

Levent Erdogan	Use of microwave energy in tar sands applications	Associate, École Polytechnique de Montréal Co-supervised by Dr. C. Akyel

Other Team Members (associates, undergraduate students, support staff)		
Oualid Hammi	Lab Manager	
Christopher Simon Tibor Bata	Technical support Technical support to students for printed circuit board (PCB) fabrication and instrumentation	
Pauline Cummings Ivana D'Adamo	Administrative support to Dr. Ghannouchi and the iRadio Lab team	

6. COLLABORATIONS

Participants	**Nature of Collaboration**
National Collaborations	
École Polytechnique de Montréal: Dr. K. Wu Dr. R. Malhame Dr. A. Cevdet	Collaboration with the Poly-Grames Research Center (Dr. K. Wu) concerns access to advanced printed circuit board (PCB) fabrication facilities by the iRadio Lab team. Moreover, three graduate students from École Polytechnique de Montréal are currently supervised by Dr. Ghannouchi.
Université de Québec: Dr. A. Kouki	The ongoing theme of collaboration is related to LINC-based amplifiers and GaN transistors modeling.
International Collaborations	

Université de Tunis (ENIT, FST, Sup'COM) , Tunisia: Dr. A. Ghazel (Sup'Com) Dr. M. Jaidane (ENIT) Dr. A. Gharsallah (FST)	The ongoing themes of collaboration are related to behaviour modeling of nonlinear systems, implementation of digital predistortion (DPD) technology using DSP/FPGA modules and the design of multi-standard receivers using RF subsampling techniques. Several joint papers have been published that report the results obtained so far. Dr. Ghannouchi is co-supervising the work of two Ph.D. candidates and one Master student.
Université de Bordeaux, France: Dr. E. Kerhervé Y. Deval	Collaboration with the IXL Laboratory of the Université de Bordeaux to study, analyze and assess the suitability of integrated multi-band RF power amplifiers. During this past year, one graduate student from Université de Bordeaux spent two terms at iRadio lab.
Ningbo University of China, China: Prof. T. Liu	Collaboration was initiated this year. Ongoing research activities are related to the modeling and compensation of memory effects in RF power amplifiers.
Amirkabir University, Iran: Prof. A. Mohammadi	Collaboration was initiated this year. Ongoing research activities on six-port receivers and MIMO wireless systems.
Industrial Collaborations	
TRLabs, Canada: Dr. R. Davis	The collaboration with TRLabs is mainly concerned with the development of an antenna selection algorithm for MIMO systems and RF front-end design for MIMO radio systems.
Canadian Space Agency, Canada: Mr. G. Brassard Mr. T. Pellerin	In the frame of a NSERC Collaborative Research and Development (CRD) grant (2007-2009), the objective of this collaboration is the development of GaN-based innovative Doherty power amplifiers intended for the Canadian Space Agency's quicksat program.
Focus Microwaves, Canada: Dr. C. Tsironis Dr Z. Ouardirhi	Focus Microwaves is sponsoring the ongoing NSERC Collaborative Research and Development (CRD) grant (2007-2009) and providing privileged technical support for our activities related to the load-pull

	characterization of active devices.
Nanowave Technologies, Canada: Dr. A. Rahal	Dr. Ghannouchi has been collaborating with Nanowave Technologies since 2006, within an 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.
Nortel, Canada: T. Dashin N.Outtaleb	The collaboration with Nortel was initiated last year. Nortel is currently supporting an NSERC strategic project related to the development of GaN-based switching-mode power amplifiers.
Rockwell Collins, Government Systems, USA: Dr. G. Hegazi	Collaboration on LINC transmitter design.
Powerwave Technologies, USA: B. Vassilakis Dr. N. Braithwaite	The collaboration with Powerwave Technologies was initiated last year. This collaboration is aimed at the modeling and linearization of Powerwave's commercial power amplifiers.
Freescale Semiconductor, USA: J. Wood	Freescale is providing LDMOS-based devices and high-efficiency PA evaluation boards of their products to be used as devices under test for the ongoing research topic related to the design of high-efficiency Doherty power amplifiers.
Nitronex, USA: P. Rajagopal B. Therrien	The collaboration with Nitronex was initiated last year. It covers the support of an NSERC strategic grant, as well as privileged access to Nitronex's GaN device technology.
RFHIC, Korea	RFHIC is providing iRadio Lab with privileged access to their GaN transistor products for characterization, modeling of power amplifiers.
Altera, USA	Altera is providing iRadio Lab with FPGA boards from their university program.
Analog Devices, USA	Analog Devices is providing iRadio Lab with DSP boards and circuits from their university

	program.
MathWorks, USA	MathWorks provided iRadio Lab free software licences for special tool boxes needed to build the SDR platform in the context of SDR challenge 2008.

7. GRADUATES

- Postdoctoral Fellows

Name	Degree	Research Topic	Current Position
Renato Negro	Ph.D	Switching-mode power amplifiers	Presently Assistant Professor, Aachen University, Germany
Souheil Bensmida	Ph.D.	Characterization of RF transistors	Presently Research Associate, Bristol University, UK
Sung-Chan Jung	Ph.D.	Doherty power amplifiers	Presently Research Professor, Sungkyunkwan University, Korea

- Ph.D. Candidates

Name	Degree	Research Topic	Current Position
Oualid Hammi	Ph.D.	Behavioural modeling and predistortion of power amplifiers	Postdoctoral Fellow, University Calgary
Mohamed Helaoui	Ph.D.	All-Digital transmitters design	Postdoctoral Fellow, University of Calgary

- M.Sc. Candidates
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Name	Degree	Research Topic	Current Position
Safar Hatami	M.Sc.	Delta-sigma RF transmitters	Ph.D. Student, University of Southern California
Farzaneh Taringou	M.SC.	Black-box behaviour modeling of wireless transmitters	Research Associate, iRadio Lab
Ramzi Darraji Co-supervised with Dr. A. Ghazel)	Master in Telecom. Sup'Com Tunisia	Design of an Integrated Multi-standard receiver	

- Research Associates

Name	Degree	Research Topic	Current Position
Peter Stacha	Ph.D.	PCB technology	Engineer in industry, Calgary

8. INTELLECTUAL PROPERTY

Intellectual Property	Status	Short Description
Patents	Applied for this year through University Technologies International, Inc. (UTI)	Mode-multiplexing LINC transmitters for wireless transmitters, US provisional patent application, April 2008.
	Applied for this year through University Technologies International, Inc. (UTI)	Nonlinear behavior models and methods for use thereof in wireless radio, US patent application (published June 5, 2008
	Applied for this year	All-digital multi-standard transmitter architectures, International patent Application (PCT/CA 2008/000060)
	Applied for this year	Multi-standard transmitter using sigma-delta modulator, US patent application, Feb. 2009.
	Granted prior to this year	"Adaptive Predistortion Device and Method Using Digital Receiver", US patent # 7,035,345, April 2006
Licenses	New	None
Spinoff Companies	GreenRadio Technologies	Area of activities: highly efficient and green RF electronics

9. PUBLICATIONS

Refereed Journal Publications

R. Barrak, A. Ghazel, and F. Ghannouchi, "Optimized Multistandard RF Subsampling Receiver Design", IEEE Transactions on Wireless Communications (accepted).

P. Aflaki, R. Negra, and F. M. Ghannouchi, "Enhanced Architecture for Microwave Current Mode Class-D Amplifiers Applied to the Design of an S-Band GaN-Based PA", IET Microwave Antenna & Propagation (accepted).

P. Aflaki, R. Negra, and F. M. Ghannouchi, "1 GHz Current Mode Class-D Power Amplifier in Hybrid Technology using GaN HEMTs", Romanian Journal of Information Science and Technology – ROMJIST (accepted).

N.S. Sani, A. Mohammadi, A. Abdipour, and F.M. Ghannouchi, "Analysis of Multiport Receivers using FDTD Technique", Journal of Electromagnetic Waves and Applicaitons (JEMWA), Volume 23, no. 5/6, 2009, pp. 635-643.

O. Hammi and F. M. Ghannouchi, "Power Alignment of Digital Predistorters for Power Amplifiers Linearity Optimization", IEEE Transactions on Broadcasting, Vol. 55, Issue: 1, Mar. 2009, pp. 109-114.

M. Helaoui and F. M. Ghannouchi, “Optimizing Losses in Distributed Multiharmonic Matching Networks Applied to the Design of and RF GaN Power Amplifier with Higher Than 80% Power-Added Efficiency”, The IEEE Transactions on Microwave Theory and Techniques. Volume 57, Issue 2, February 2009 Pages 314-322.

S. Jung, R. Negra, and F. M. Ghannouchi, "A Design Methodology for Miniaturized 3 dB Branch-Line Hybrid Couplers Using Distributed Capacitors Printed in Its Inner Area", IEEE Transactions on Microwave Theory and Techniques, Vol. 56, Dec. 2008, pp. 2950-2953.

O. Hammi, S. Carichner, B. Vassilakis, and F.M. Ghannouchi, "Power amplifiers’ model assessment and memory effects intensity quantification using memoryless post compensation technique", IEEE Transactions on Microwave Theory and Techniques, Vol. 56, Issue: 12, Part: 2, Dec. 2008, pp. 3170-3179.

R. Negra, F. M. Ghannouchi, and W. Bächtold, "Analysis and Evaluation of Harmonic Suppression of Lumped-Element Networks Suitable for High Frequency Class-E Operation Condition Approximation", IET Microwaves, Antennas & Propagation, Vol. 2, Issue 8, Dec. 2008, pp. 794-800.

O. Hammi, S. Carichner, B. Vassilakis, and F. M. Ghannouchi, "Synergetic Crest Factor Reduction and Baseband Digital Predistortion for Adaptive 3G Doherty Power Amplifier Linearizer Design", IEEE Transactions on Microwave Theory and Techniques, Vol. 56, Issue: 11, Part: 2, Nov. 2008, pp. 2602-2608.

M. Helaoui, S. Hatami, R. Negra, and F.M. Ghannouchi, "A Novel Architecture of Delta-Sigma Modulator enabling All-Digital Multiband Multistandard RF Transmitters Design", IEEE Transactions on Circuits and Systems II, Nov. 2008, pp. 1129-1133.

A Kwan, M. Helaoui, S. Boumaiza, M.R. Smith, and F. Ghannouchi, "Wireless Communication Transmitters' Performance Enhancement using Advanced Signal Processing Algorithms Running in Hybrid DSP/FPGA Platform", The Journal of VLSI Signal Processing-Systems for Signal, Image, and Video Technology, DOI 10.1007/s11265-008-0225-3, May 2008.

F. M. Ghannouchi, "Software Defined Radio Transmitters for Advanced Wireless and Satellite Communications Systems", Microwave Journal, Vol. 51, Issue: 5, May 2008, pp. 202-216.

O. Hammi, F. M. Ghannouchi, and B. Vassilakis, "A Compact Envelope-Memory Polynomial for RF Transmitters Modeling with Application to Baseband and RF-Digital Predistortion", IEEE Microwave and Wireless Component Letters, Vol. 18, Issue: 5, May 2008, pp. 359-361.

O. Hammi, F. M. Ghannouchi, and B. Vassilakis, "On the Sensitivity of RF Transmitters' Memory Polynomial Model Identification to Delay Alignment Resolution", IEEE Microwave and Wireless Component Letters, Vol. 18, Issue: 4, Apr. 2008, pp. 263-265.

L. Degachi and F. M. Ghannouchi, "An Augmented Small-Signal HBT Model with its Analytical Based Parameter Extraction Technique", IEEE Transactions on Electron Devices, Vol. 55, Issue: 4, Apr. 2008, pp. 968-972.

Refereed Conference Proceedings

R. Negra, F.M. Ghannouchi, and W. Bächtold, "Monolithic lumped-element unequal branch-line coupler for the use in asymmetrical Doherty amplifiers", IEEE Topical Symposium on Power Amplifiers for Wireless Communications, San Diego, CA, January 2009.

O. Hammi, S. Carichner, B. Vassilakis, and F. M. Ghannouchi, "On the Predistortability of High Efficiency Multi-carrier Power Amplifiers for Wireless

Communication Infrastructure", IEEE Topical Symposium on Power Amplifiers for Wireless Communications, San Diego, CA, January 2009.

P. Aflaki, R. Negra and F.M. Ghannouchi, "Proper balun structures for microwave current mode class-D switching-mode power amplifiers", IEEE Topical Symposium on Power Amplifiers for Wireless Communications, San Diego, CA, January 2009.

O. Hammi, M. Younes, B. Vassilakis, and F.M. Ghannouchi, "Digital predistorters sensitivity to delay alignment resolution," 2009 IEEE Radio and Wireless Symposium (RWS 2009), San Diego, CA, January 2009, pp. 606-609.

P. Aflaki, H.G. Bae, R. Negra, and F.M. Ghannouchi, "Novel Compact Transmission-line Output Network Topology for Class-E Power Amplifiers", 38th IEEE European Microwave Conference (EuMC2008), Amsterdam, Netherland , October 2008, pp. 238-241.

S. Bensmida and F. M. Ghannouchi, "A New High Directivity Coupler Design Using Feedforward Compensation Techniques", 38th IEEE European Microwave Conference (EuMC2008), Amsterdam, Netherland, October 2008, pp. 191-194.

S. Saied Bouajina, M. Jaidane, and F. M. Ghannouchi, "Weighted Criteria for RF Power Amplifiers Identification in Wide-band Context", 2008 IEEE International Conference on Electronics, Circuits and Systems (ICECS2008), Malta, August 2008, pp. 173-176.

T Liu, Yan Ye, Zhiwei Fan, Xingbin Zeng, F. ghannouchi. “Linearization of Wideband RF Doherty Power Amplifiers with Complex Dynamic nonlinearities.” Communications and Networking in China, 2008. ChinaCom 2008. Third International Conference on 25-27 August, 2008 pages 974-977.

R. Darraji, A. Ghazel, and F.M. Ghannouchi, "Integrated Track-and Hold Circuits for SDR Receivers", 2008 IEEE International Conference on Electronics, Circuits and Systems (ICECS2008), Malta, August 2008, pp. 1249-1252.

J. Li, O. Hammi, and F. M. Ghannouchi, “Implementation of Dual-channel Receiver Suitable for 3G Power Amplifiers Characterization in RF/Digital Predistortion Systems", 2008 IEEE International Conference on Electronics, Circuits and Systems (ICECS2008), Malta, August 2008, pp. 169-172.

S. A. Bassam, M. Helaoui, S. Boumaiza, and F. M. Ghannouchi, "Experimental Study of the Effects of RF front-end imperfection on the MIMO Transmitter Performance", 2008 IEEE MTT-S International Microwave Symposium (IMS2008), Atlanta, GA, June 2008, pp. 1187-1190.

O. Hammi, S. Carichner, B. Vassilakis, and F.M. Ghannouchi, "Novel Approach for Static Nonlinear Behavior Identification in RF Power Amplifiers Exhibiting Memory Effects", 2008 IEEE MTT-S International Microwave Symposium (IMS2008), Atlanta, GA, June 2008, pp. 1521-1524.

S. Bensmida, F.M. Ghannouchi, and E. Bergeault, "An Original Setup for Power Amplifier AM-AM and AM-PM Characterization", 2008 IEEE Instrumentation and Measurement Technology Conference (I2MTC), Vancouver, BC, May 2008, pp. 54-57.

W.S. El-Deeb, S. Bensmida, and F.M. Ghannouchi, "A De-embedding Technique for On-wafer Simultaneous Impedance and Power Flow measurements", 2008 IEEE Instrumentation and Measurement Technology Conference (I2MTC), Vancouver, BC, May 2008, pp. 58-61.

P. Aflaki, R. Negra, A. Mohammadi, and F.M. Ghannouchi, "A New Approach to Design Frequency Synthesizer Using Direct Digital Synthesis Technique", 2008 IEEE Canadian Conference on Electrical and Computer Engineering, Niagara Falls, ON, May 2008, pp. 1733-1736.

T. Liu, Y. Ye, X. Zeng, and F.M. Ghannouchi, "Memory Effect Modeling of Wideband Wireless Transmitters Using Neural Networks", 2008 IEEE International Conference on Circuits and Systems for Communications, Networking and Mobile Computing (ICCSC2008), Shanghai, China, May 2008, pp. 703-707.

T. Liu, Y. Ye, X. Zeng, and F.M. Ghannouchi, "Accurate Time-Delay Estimation and Alignment for RF Power Amplifier/Transmitter Characterization", 2008 IEEE International Conference on Circuits and Systems for Communications, Networking and Mobile Computing (ICCSC2008), Shanghai, China, May 2008, pp. 70-74.

T. Liu, Y. Ye, S. Boumaiza, M. Helaoui, O. Hammi, and F.M. Ghannouchi, "Accurate Identification of Static Nonlinear Properties of Wideband RF Power Amplifiers", 6th International Conference on Microwave and Millimeter Wave Technology, Nanjing, China, Vol. 3, April 2008, pp. 1351-1354.

T. Liu, Y. Ye, S. Boumaiza, M. Helaoui, O. Hammi, and F.M. Ghannouchi, "Accurate Modeling of Wideband RF Power Amplifiers using Dynamic Nonlinear Models", 6th International Conference on Microwave and Millimeter Wave Technology, Nanjing, China, Vol. 3, 21-24 April 2008, pp. 1363-1366.

T.Liu, Y. Ye, S. Boumaiza, and F.M. Ghannouchi, "Rapid behavior Modeling Platform for RF Power Amplifiers/Transmitters", 6th International Conference on Microwave and Millimeter Wave Technology, Nanjing, China, Vol. 2, April 2008, pp. 918-921.

Books and Chapters

Six-Port Techniques with Microwave and Wireless Applications, F.M. Ghannouchi and A. Mohammadi, Editor Artech House: (In press)

Special/Invited Presentations

F. M. Ghannouchi, "Power Amplification for Advanced Transmitter Architectures: an Overview", invited IEEE sponsored talk, University of Calgary, July 2, 2008.

O. Hammi and F.M. Ghannouchi, "Automated solutions for power amplifiers modeling and digital predistorters synthesis", invited presentation, Powerwave Technologies Inc, Santa Ana, CA, August 15, 2008.

O. Hammi, M. Helaoui, and F. M. Ghannouchi, "Advanced Transmitters Technology for 4G Applications", invited presentation, Samsung, USA, September 24, 2008.

F. M. Ghannouchi, "Advanced Power Amplifier / Transmitter architectures for Wireless and Satellite Communications", invited talk as an IEEE MTT-S Distinguish Microwave Lecturer, Kassel University, Germany, October 19, 2008.

F. M. Ghannouchi, "Advanced Power Amplifier / Transmitter Architectures for Wireless and Satellite Communications", invited talk as an IEEE MTT-S Distinguish Microwave Lecturer, Aachen University, Germany, October 21, 2008.

F.M. Ghannouchi, "Advanced Power Amplifier / Transmitter Architectures for Wireless and Satellite Communications", invited talk as an IEEE MTT-S Distinguish Microwave Lecturer, Vienna Technical University, Austria, October 23, 2008.

O. Hammi and F.M. Ghannouchi, "Predistortion Technology for 3G Base Stations", invited presentation, Mitsubishi, Tokyo, Japan, November 27, 2008.

F. M. Ghannouchi, "Software Define Radio with Applications to Broadband Communications", keynote speech, International Symposium on Microwaves 2008, Bangalore India, December 5, 2008.

F.M. Ghannouchi, "Advanced Power Amplifier / Transmitter Architectures for Wireless and Satellite Communications", invited talk as an IEEE MTT-S Distinguish Microwave Lecturer, San Diego, CA, January 7, 2009.

F. M. Ghannouchi, "SDR is an Enabling Technology for the Convergence Communications of Networks", keynote speech, International Conference on Communications, Computer and Power (ICCCP'09), Muscat, Oman, February 17, 2008.

F. M. Ghannouchi, "SDR Technology for Wireless and Satellite Communications", invited talk, IEEE MTT-S Distinguish Microwave Lecturer, Ottawa, ON, March 6, 2009.

Workshops and Short Courses

M. Helaoui and F.M. Ghannouchi, "Recent Advances in LINC Amplification Systems", IMS 2008 Workshop on Highly Efficient Linear Power Transmitters for Wireless Applications based on Switching Mode Amplifiers, Atlanta, GA, June 16, 2008.

O. Hammi, F. M. Ghannouchi, T. Liu, and A. Kwan, "Digital Predistortion: An Enabling Technique for 4G Transmitters Design", in 38th IEEE European Microwave Conference (EuMC2008), Amsterdam, Netherlands, October 2008.

O. Hammi and F. M. Ghannouchi, "Recent advances in predistortion technology with applications to 3G base station power amplifiers", Microwave Workshop and Exhibition (MWE2008), Pacifico Yokohama, Japan, November 2008.

F. M. Ghannouchi, "Software Define Radios: Design Architectures & Efficient Transmitters", tutorial, International Symposium on Microwaves 2008, Bangalore, India, December 4, 2008.

F. M. Ghannouchi, "Behavioral Modeling and Digital Predistortion of Wideband Wireless Transmitters", tutorial, Sultan Qaboos University, Muscat, Oman, February 15, 2009.

Non Refereed Conference Papers

None

Posters

None

Seminars

iRadio Lab continues to organize biweekly seminars where graduate students and research staff present and discuss the latest results of their work. Abstracts of these seminars may be found at
http://iradio.ucalgary.ca/seminars/lab_seminars .

10. OUTREACH

The community outreach activities of iRadio Lab included:

- iRadio Lab students participated in SDR Challenge 2008 (http://www.radiochallenge.org/08Challenge.html), Washington, DC, October 24, 2008, and won first place for problem 3.

- Professor Ghannouchi was the lead off story for CTV News on December 18, 2008 covering the topic of energy consumption and the reduction of green house gas emissions associated with cell phone use and wireless base stations.

- The lead article of the Schulich School of Engineering Magazine Fall 2008 issue was devoted to Dr. Ghannouchi's research activities related to green electronics.

- CBC News published an article on iRadio Labs' efforts on the development of energy-saving radio systems being conducted at iRadio Lab.

11. FINANCIAL REPORTS

1. iCORE REVENUES/EXPENSES

The annual financial statement will be sent directly to iCORE by the Financial Services of the University of Calgary.

2. FUNDING SOURCES

The funding sources report lists all of our active funding sources. The provided spreadsheet for this purpose was updated to reflect the cash and in-kind funds obtained in this year. This spreadsheet is attached with this report.

Funding Sources

- iCORE

- Alberta Government (ASRA, other)
- University of Calgary (cash)
- University of Calgary (in-kind)
- Industry (cash)
- Industry (in-kind)
- Canada Research Chair
- Canada Foundation for Innovation
- Natural Sciences and Engineering Research Council of Canada
- Other Federal Government
- Other Government

PUBLISHED ANNUAL RESEARCH REPORT

1. REPORT IMAGES OR PHOTOS

Attached photos are provided which can use for the published version of the annual report.

For the published version of the Annual Research Report, please provide separate copies of all referenced images included in your report.

Ideally your images should be:
- at least 6"x 4"
- at least 300 dpi
- in cmyk colour mode

Acceptable file formats in order of preference are: tiff, eps, jpg