iRadio Laboratory Annual Report
FADHEL GHANNOUCHI
AITF Professor in Intelligent RF Radio and CRC Chair (Tier 1)
Electrical and Computer Engineering, University of Calgary

1. EXECUTIVE SUMMARY

The Informatics Circle of Research Excellence (iCORE) professorship program in Intelligent RF Radio Technology was launched on May 1st, 2005, leading to the establishment of the Intelligent RF Radio Laboratory (iRadio Lab, http://www.iradio.ucalgary.ca/) in the Department of Electrical and Computer Engineering of the Schulich School of Engineering at the University of Calgary. Following the research program's successful achievements, a renewal of the professorship was granted by Alberta Innovates Technologies Futures (AITF) for an additional five-year period starting May 1st, 2011. The present research program is a continuation and reinforcement of the research and development (R&D) activities conducted at iRadio Lab during its first six-year period. These activities have led to the recognition and positioning of the University of Calgary as an emerging world-class research institution in the area of RF (radio frequency) radio systems. The main objective set for iRadio Lab's second mandate is to build on the success of past achievements to seamlessly align the R&D activities toward gigabit (Gbit) software-defined radio (SDR) and multiple input, multiple output (MIMO) systems. The planned research program for this five-year period is concerned with microwave and millimetre-wave (mm-wave) devices, circuits and systems, Gbit digital and mixed electronics, adaptive digital signal processing, modeling of devices, channels and systems, linearization and equalization concepts, space diversity techniques and MIMO systems, software-hardware implementation and integration issues, design and realization of circuits and systems with hybrid and integrated technologies, and other related applications.

iRadio Lab is already staffed with more than twenty graduate students and talented researchers, who have been recruited worldwide. The main space dedicated to iRadio Lab in the University of Calgary's ICT building (ICT 305) is being used as offices for graduate students and research staff, as well as the main instrumentation, simulation and design area. An additional space (ICT 318) was provided last year by the Department of Electrical and Computer Engineering to accommodate the expansion of the R&D activities and host the additional graduate students and researchers planned for this five-year period. An auxiliary space in A Block of the Engineering Building (ENA 5), which is used for printed circuit board fabrication and prototyping, is also being utilized by graduate students and researchers. iRadio Lab's facilities are supported by a number of test benches and rapid prototyping setups and by computer-aided design (CAD) based software.

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 the wireless communications industry and government R&D agencies. iRadio Lab has close formal collaborations with several national and international academic institutions, industry partners and government agencies..

The innovative and application-oriented R&D activities being carried out at iRadio Lab have led to thirty-nine refereed journal papers (published and accepted), twenty-six refereed conference papers, one patent, three patent applications and the publication of one book. Nine keynote and invited talks were given by iRadio Lab researchers at international conferences and leading research institutions and universities. A Ph.D. student from iRadio Lab was awarded the Teledyne DALSA Componentware / CAD Award during the CMC TEXPO Event (a research competition) and the

Analog Device, Outstanding Student Design Award at the IEEE International Solid-State Circuits Conference, San Francisco, February 22, 2012.

During its fifth year, iRadio Lab was successful in securing substantial funding: $270K from the Natural Sciences and Engineering Research Council of Canada (NSERC), and $60K from industry. These monies supplement the $850K, $200K and $150K yearly averages provided by AITF, the Canada Research Chairs (CRC) program and the University of Calgary, respectively. In addition, in-kind contributions and equipment donations and loans in the amount of about $60K from industry partners and $200K of in-kind contributions from the University of Calgary have been obtained during the reporting period. Furthermore, many students have been awarded scholarships and fellowships over the years, totalling an annual average of $100K.

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 iRadio Lab personnel directly affiliated with the University of Calgary currently includes two fully affiliated faculty members, two associated faculty members, two technical support staff, one administrative support staff, one lab manager, four postdoctoral fellows and eighteen graduate students.

Research Partners

iRadio Lab has been mainly funded by joint sponsorship from AITF, CRC, NSERC and the Canada Foundation for Innovation (CFI). Formal academic collaborations are maintained with Canadian and international universities in the areas 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. Semiconductor technology (Freescale Semiconductor, Nitronex, Cree);

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

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

Major Research Directions

The scope of this AITF/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 digital signal processing (DSP) and mixed signal technology, microwave and mm-wave technology, and communications systems, including the manufacturing processes and implementation 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 Microwave / MM-Wave 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 an RF/DSP co-design approach, in order to ensure desired functionality and optimal system-level performance. This includes impairment pre-compensation and architecture-dependent signal processing and conditioning.

Adaptive and Reconfigurable Receivers: This is the counterpart of the multiband transmitter required for software-defined high-performance transceivers. New architectures are considered critical for the development and deployment of multi-frequency, multistandard communications systems.

Software-Defined Radio: The design of multi-band, multimode 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.

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 research proposal submitted to AITF, 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 green multi-standard broadband communication systems. The optimization of power-added efficiency, due mainly to the reduction in 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 relation to the main initial goals relevant to this project.

Microwave and Radio Frequency Devices Characterization and Modeling

Due to their high output power delivery capability at microwave frequencies, good linearity, high power efficiency and low self-heating, gallium nitride (GaN) transistors are the superior choice for microwave switching-mode power amplifier (PA) design. Switching-mode PAs can theoretically achieve up to 100% efficiency, and it has been reported that an efficiency higher that 70% can be attained in practical designs. In order to facilitate the design process and improve the PA's performance, a simple switch-based model was introduced to predict the behaviour of GaN switching-mode PAs. This model is accurate in the saturation region, but it loses accuracy in the back-off region. In order to improve the model accuracy, the following modifications and studies have been performed during the past year, in close collaboration with academic (École de Technologie Supérieure (ETS), Université du Québec) and industrial partners (National Research Council Canada, NRC, and Canadian Microelectronics Corporation, CMC):

- The effect of different order approximations of the model components, including intrinsic capacitors and drain and gate current sources, on the accuracy of the GaN switch-based transistor model performance was investigated. According to this study, a switching-mode PA designer is able to make a tradeoff between model accuracy and model complexity.

- In order to enhance the accuracy of the switch-based model, the drain current source in the circuit model was built using a data table obtained from transistor DC-IV (direct current, current voltage) measurements. This improves the accuracy and extends the model operating region to the lower input powers, since real data is used to predict the transistor behaviour.
- To further improve the analytically based model, two terms were added to the original drain current equation borrowed from LDMOS (laterally diffused metal oxide semiconductor) transistor modeling, in order to capture the trapping and thermal effects. The kink effect was also added to the drain current equation, and a parallel thermal resistor with the current source was employed to model the self-heating thermal effect. The accuracy improvement was verified by comparing this model performance with the previous model performance and fabricated PA measurement results.

Green RF Power Amplification Systems

The objective of this research project is the design of energy efficient broadband transmitters for the emerging communication standards (third generation and beyond). The activities carried out within this project of multiple input digital Doherty PAs have been performed in close collaboration with the Canadian Space Agency (CSA), CMC and Université du Québec.

In continuation of work done in previous years on the design of digitally driven Doherty PAs, two GaN Doherty PA prototypes were successfully tested, exhibiting excellent efficiency performances. In the first design, the performance was improved through the implementation of a digital adaptive phase alignment mechanism that entirely compensated for the dynamic phase disparity problem. In the second digital Doherty PA prototype, the efficiency enhancement was achieved by using a digitally controlled adaptive input power distribution scheme that was derived to reduce the drive power waste into the peaking branch at back-off power levels and to compensate for the gain imbalance problem. Average drain efficiencies of higher than 50% were achieved using realistic communication signals (Worldwide Interoperability for Microwave Access, WiMAX, and Wideband Code Division Multiple Access, WCDMA). In addition, a practical methodology was successfully implemented to linearize the multiple input digital Doherty PAs, evolving towards a fully linear, highly efficient digital Doherty transmitter.

After experimentally validating the operation of the novel topology of the dual-input digital Doherty PA, further works were carried out to investigate the possibility of using DSP for mitigation of bandwidth limitation in wireless Doherty PAs. In this context, a new methodology for extending the bandwidth of Doherty PAs in the digital domain was proposed. Bandwidth enhancement is achieved through a frequency selective, pre-compensation mechanism that is derived to prevent the efficiency degradation that naturally occurs as the frequency of operation deviates from the centre frequency. Applied to a GaN Doherty PA prototype with a nominal bandwidth of 180 MHz, the proposed technique allowed for the achievement of a bandwidth of 500MHz.

The activities carried out within this project are supported through an NSERC Collaborative Research Development grant and an NSERC Strategic Program grant.

Advanced Adaptive DSP Algorithms for Wireless Transceivers

For better communication with next generation signals, many solutions have been proposed to mitigate transmitter imperfections, such as power amplifier (PA) nonlinearity, in-phase/quadrature-phase (I/Q) imbalance, and DC offsets. In practice, signal distortions due to modulator imperfections and PA nonlinearity are compensated separately, which requires additional control loops and RF components to sample at the amplifier output stage. These complications are compounded when using higher bandwidth, multiple bands or multiple transceiver designs.

Advanced digital predistortion (DPD) architectures based on Volterra models (the cross-coupled gain simplified Volterra model) and artificial neural network models (the two hidden layer focused time delay real valued feedforward network) have been investigated and successfully tested for practical imbalance limits, which allows for a one-step DPD solution for PA nonlinearity, as well as I/Q imbalance for wideband direct conversion transmitters. It has been observed that, for the same performance, the cross-coupled gain simplified Volterra model offers a simple technique compared to neural network based solutions; however, it has been found that neural networks provide better flexibility, because the same topology and parameters handle any amount of gain imbalance and hardware impairments.

Apart from the above batch-mode solutions, a novel distributed spatio-temporal neural network is under investigation for its robustness in the presence of modulator imperfection. It has been observed that, with this neural network where nonlinearity is distributed in space as well as time, adaptive predistortion has much faster convergence and less complexity than state-of-the-art adaptive solutions that provide data-to-data adaptation. It is estimated that, once this network is implemented in a dedicated digital signal processor, significant savings on digital processing computational power can be achieved, compared to batch-mode solutions and the existing sequential mode solutions.

A novel feedforward Hammerstein model has been proposed for the accurate modeling and predistortion of PA dynamic distortion. The model is composed of two coupled loops: the signal cancellation loop and the distortion injection loop. The main signal cancellation loop of this model is composed of a Hammerstein model, in order to characterize the PA's static nonlinearities and linear memory effects. The nonlinear memory effects are characterized through the distortion injection loop, which accurately models the intermodulation-distorted signal that results from subtracting the Hammerstein model output from the PA input. This distorted signal is modeled by a set of parallel linear filters. The additional loop further improves model performance.

Multiple input, multiple output (MIMO) systems are seen as a viable alternative to increase transmitter diversity and bandwidth. A transmitter's PAs may cause coupling on the each path and produce interference on the wireless signal, in addition to I/Q imbalance and DC offset effects. Research has been conducted on the linear and nonlinear crosstalk derived from a two-channel system; and, a technique has been derived based on a multivariate polynomial model that, when used as a digital predistorter, shows considerable improvement for systems that present these interference effects.

Wireless cellular systems use multi-band transceivers that allow for multi-standard communications. Typically, amplifiers are needed for each band; however, the design of dual-band amplifiers shows promise in maintaining high efficiency on their respective bands and aims to reduce the number of components in cellular devices. The application of different RF signals on a single transistor causes similar coupling problems for the MIMO case, and the distortion is severely increased when transmitting in both bands at the same time. Memory effects caused by wide bandwidth signals also increase the modeling and linearization difficulty. Extraction of the modulation products between these two signals has been investigated and is of critical interest when developing linearization techniques for dual-band PAs.

These projects are supported by the AITF research grant and the CRC grant and have been performed in close collaboration with industrial partners.

Multi-Band and Multimode SDR-Based Transmitters

This research project mainly focuses on the development of software-defined radio (SDR) based transceivers that are able to adapt to multiple communication standards using the same hardware platform. The intention is that the hardware platform can be targeted for multi-band, multi-standard and multi-antenna applications that can be quickly controlled through the ease of software reconfigurability. In the context of a reconfigurable baseband transmitter platform, we have proposed multi-standard, multi-mode SDR-based transmitters that incorporate a dual-band PA, based on the high-efficiency Doherty amplifier and a channel selective digital predistortion (DPD) system for linearization purposes. The amplifier design has been fabricated and tested. A new dual-band predistortion methodology has already been established and is being implemented in a field-programmable gate array (FPGA) -

based digital signal processing (DSP) platform. A similar RF-DPD platform suitable for dual-band application in repeaters has been developed and is under evaluation.

The dual-band Doherty PA presents challenges in designing a dual-band passive component and a dual-band matching strategy. So far, there have been no complete solutions in dual-band matching topology for the design of a high-efficiency PA. Thus, a thorough investigation has been done as a part of this research; and, a novel idea has been proposed, based on dual-band/dual-impedance quarter wave transformers. Due to their dispersive phase characteristic and varying image impedance, such transformers have shown potential for matching a high-power device to two arbitrary reflection coefficients at two different bands. These reflection coefficients are optimal, in terms of achieving power efficiencies at two distinct bands; hence, such matching can provide optimal performance in the two distinct bands. Further research is under progress using matching topology to improve the performance of existing dual-band Doherty architecture. To identify and characterize the nonlinear behaviour of the proposed dual-band Doherty PA, multi-tone excitation signals were used; and, the memory effects of the modulation products were also evaluated. Compared to a conventional single-band PA, the concurrent dual-band PA has exhibited additional cross-modulation terms, except for traditional intermodulation. Consequently, the linearization scheme should jointly deal with the dual-band PA's intermodulation and cross-modulation distortions, which are commonly caused by in-band and cross-band signals.

A two-dimensional DPD linearization (2D-DPD) technique, which compensates for dual-band distortions, has been proposed for the first time and has been used to linearize the dual-band Doherty PA described above. By considering the complex envelopes of both input signals in the model identification process, a processing model was developed, so that both input signals have contributions in the model identification process. This architecture reduces the requirement for the sampling rate of an analog-to-digital converter (ADC), since it deals with the dual-band signals separately. In our study, two kinds of nonlinear behavioural models have been developed for nonlinear PA modeling and linearization. Due to the good performance of memory polynomials, a two-dimensional (2D) memory polynomial has been proposed. By introducing cross terms with memory effects in the polynomial, the nonlinearity induced by cross-modulation can be compensated for effectively. Moreover, in order to deal with wild nonlinearities in concurrent dual-band PAs, as well for concurrent dual-band PA modeling, an RVTDNN (real-value time-delay neural network) based model has been developed, which has achieved performances comparable to those of 2D memory polynomials.

Carrier aggregation enabled transmitter architecture has been developed based on our concurrent dual-band PA and the 2D-DPD platform, with an energy efficient multi-band transmitter architecture proposed for carrier aggregation (CA) in the LTE-Advanced (Long Term Evolution Advanced) standard. There are two advantages to using multi-band transmitter topology over that of multiple RF chains. First, the isolated power combiners in both topologies are passive components, which contribute to power loss; and, some of the signal power is dissipated in the power combiner. Considering the position of the power combiners, either after or before the PA, the amount of power consumed in the multiple RF chain model is in the tens of orders of magnitude higher than that of the multi-band transmitter. This significantly reduces the power loss in the system and improves the transmitter's power efficiency. Second, in inter-band CA, there are scenarios in which there is no active signal in one of the frequency bands. To reduce the power consumption and improve the power efficiency, there is a need for a controlling mechanism to turn the inactive RF chains on and off, so that such controlling units can be omitted from the multi-band transmitter.

The fully digital transmitter project allows for the adaptability and reconfigurability of several communication standards driven by a software-defined radio (SDR) interface. The heart of the digital transmitter is delta-sigma architecture, with parallel processing, in order to improve signal processing speed. We have extended the fully digital transmitter project to include enhancements, such as support for wider signal bandwidths and selection of carrier frequencies up to 5 GHz. These improvements allow the prototype to interoperate with current wireless standards, as well as the next generation of high-speed wireless communication protocols, such as WiMAX and LTE.

The multiple input, multiple output (MIMO) transmitter investigation has continued this year. This work targets performance improvement based on our recently proposed multi-cell processing technique and cross-over digital predistortion (CO-DPD, for which a patent has been recently filed). It was shown and validated that the CO-DPD technique can compensate for a transmitter's nonlinearities and nonlinear RF crosstalk. The cross-over multi-cell model has also been extended to the forward modeling of the MIMO nonlinear system; and, it has been shown that the new model can better predict the nonlinear behaviour of the MIMO system. The overall effects of the nonlinear and linear RF crosstalk and the transmitter's nonlinearities on the bit-error-rate (BER) performance of the MIMO system have been studied. The simulation results have shown that the effects of the RF nonlinearities at the transmitter need to be assessed carefully; otherwise, they may degrade the overall performance of the system. Extending the idea of using a multi-cell processing technique for the compensation of nonlinearities of a multi-band, multi-carrier RF transmitter is under investigation. The initial results show that utilization of the multi-cell processing technique can significantly reduce the minimum required sampling rates of analog-to-digital converters (ADC) and digital-to-analog converters (DAC), without performance degradation of the nonlinearities' compensation.

These projects are supported by the AITF research grant and an NSERC grant and have been performed in close collaboration with industrial partners.

Adaptive and Tuneable Receivers

Many radio applications require the capture and decoding of multiple RF bands. Synthesizing a receiver that captures a large amount of RF bands may be a good idea, but the implementation of circuitry or high-speed processing is difficult. Instead, allowing for adaptive and/or tuneable receivers provides radio systems with frequency flexibility. These receivers may be built using either wide bandwidth low-sampling analog-to-digital converters (ADCs) or multi-port interferometers circuit based techniques.

Subsampling Receivers: Currently, commercial ADCs have a pattern where high-resolution, high sampling frequency results in higher cost. A subsampling technique may be used where a low sampling frequency track-and-hold device generates aliases of the RF band signal, and a low-speed ADC is used to capture the lowest frequency alias of the RF signal. This requires calculations to ensure that no other aliases overlap and cause signal distortions. The effect of this aliasing also folds the noise in each respective band, reducing the signal-to-noise ratio (SNR). A suggestion for the use of two track-and-hold devices has been presented, where the effect is an attempt to increase the SNR. Since two stages of subsampling are used, these frequencies must be carefully analyzed, in order to achieve the highest SNR at the digital processing stage, while taking into account the clock jitter and noise folding effects.

The advantages of subsampling receivers can be shown in cognitive radio and amplifier linearization applications. In radios, wireless standards are imposed with a fixed frequency allocation where they must operate. Some of these frequency channels are used more than others, causing channel congestion where too many transmissions may interfere with each other. Cognitive radios aim to reduce these loads by spreading wireless traffic over several channels. A wideband receiver is required for these applications; however, if the bands are known, a low-speed high-bandwidth ADC is suggested to sense the underused channels and reduce costs. An approach, where changing the ADC frequency causes the receiver to sense different RF bands, has been developed for a subsampling receiver to sense up to 14 different RF bands.

The utilization of dual-band PAs and digital predistortion (DPD) typically requires two transmitters for the bands and two receivers in the feedback loop. A study have been conducted that shows the digital predistorter is able to achieve equivalent linearization performance and meet the spectrum mask requirements, when the traditional feedback loop with two receivers is replaced with a high bandwidth ADC subsampling receiver. Measurements conducted on two different PAs and a variety of communication signal standards have validated the robustness of the receiver.

Ultra-Wideband Six-Port Based Direct Conversion Receivers: The next part of this project focuses primarily on the use of the six-port technique for direct down-conversion of the RF signals to the baseband. Six-port networks are passive microwave circuits that are highly linear and can be designed to be ultra-wideband (UWB). The ongoing project on UWB signal down-conversion topology using a passive six-port network has seen interesting progress. The use of only passive components not only reduces the power consumption in the receiver side, thereby increasing the battery life in mobile communications, but also allows for the design of a UWB receiver that can be used for multi-standard and multi-carrier frequencies. In addition, this topology is highly linear and, thus, eliminates the nonlinear distortions introduced by conventional diode-based mixers. A prototype of the UWB receiver (2 GHz to 18 GHz) has been assembled and tested at different frequencies for WiMAX and LTE applications.

A new signal processing algorithm for nonlinear calibration of a receiver system and impairment compensation has been investigated. The use of a nonlinear calibration approach showed significant improvement in the signal quality at the baseband block of the receiver. Look-up table (LUT) based predistortion was used as a first step to compensate for the static nonlinear behaviour of the power detectors. This linearization further improved the quality of the received signal to reach a signal quality comparable with a state-of-the-art receiver using active components. Another new one-step integrated linear calibration procedure for a six-port receiver and linearization of diode power detectors has been proposed. This method calibrates the six-port receiver as well linearizing the diode power detectors. The new integrated linear calibration approach significantly improves the overall system performance and reduces the calibration and linearization efforts.

It has been found that the behaviour of a diode power detector is dependent on the input excitation signal type. To verify this fact, a diode power detector was used as a peak power detector; and, two new linearization techniques for the use of a diode power detector in peak power detection were proposed. A new dynamic linearization algorithm for diode power detectors, which significantly improves the diode detector performance, has been investigated. Conventional static linearization of diode power detectors is modified for the purpose of dynamic linearization, accounting for the frequency response and memory effects of the diode power detectors. The newly developed dynamic models for the diode detectors have been used to devise a new six-port receiver model for a six-port that significantly improves the overall six-port receiver performance. This new model calibrates for all the identified imperfections in the six-port based receiver system. This new model also increases the dynamic range of the whole receiver system from the minimum sensitivity level of the diode power detectors to their maximum power handling capability.

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

SDR Transmitters

The study of a 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 in tackling the implementation issues in delta-sigma modulators for the GHz range. Two of the promising advantages of fully digital transmitter architecture are its flexibility and reconfigurability, making it suitable for software-defined radio (SDR) applications. The concept of SDR is the ability to switch between the settings of different standards through software without any changes in hardware. The fully digital transmitter can provide a programmable platform for radio systems.

Time-Interleaved Delta-Sigma Transmitters: In a fully digital transmitter, it is required that all the important blocks, such as the frequency up-converter and the PA, be designed and implemented in the digital domain. In such architecture, by using an oversampled delta-sigma modulator right before the in-phase/quadrature-phase (I/Q) modulator, the signal changes to a bi-level constant envelope signal. For up-converting the signal to higher frequencies, a high-speed multiplexer can be used. This digital bi-level signal is ideal for driving a very highly efficient switching-mode PA; however, there is a drawback that should be addressed – the speed required for the oversampled delta-sigma modulator. The parallel processing technique using time-interleaved modulators is one solution to alleviate this limitation. A time-interleaved sigma delta-sigma transmitter was developed to reduce the requirement of oversampling and processing frequency and/or to extend the actual frequency bandwidth of the signal that can be handled.

Multilevel Delta-Sigma Based Transmitters: Implementation and validation of wider band delta-sigma modulators for GHz frequency applications have been made possible with parallel processing techniques and high-speed multiplexers. However, the power efficiency of these architectures tends to be relatively low. Multilevel delta-sigma architecture is a promising solution for the enhancement of the power efficiency of such transmitters, and it has been investigated and thoroughly studied during the last year. This study led to the proposal of a new delta-sigma architecture based on a multilevel quantization scheme, and preliminary results have shown its potential in achieving high efficiency. The implementation of this architecture requires a special design of the transmitter's RF front-end, mainly the multi-branch amplification section and the power combining section, which will be carried out during the next year.

In order to further enhance the transmitted signal fidelity along with improving the transmitter efficiency, a multilevel delta-sigma modulation based transmitter architecture was fully designed and measured. The transmitter showed good linearity and efficiency with a considerable decrease in the complexity of the transmitter when a discrete-level-adjustment (DLA) algorithm was utilized instead of using fully digital predistortion.

Noise Shaping Techniques for Delta-Sigma Modulators: The efficiency enhancement of delta-sigma based transmitters is addressed in our recent research. While the presence of quantization noise hinders the achievement of maximum efficiency of a switching-mode PA, it is still tempting to use delta-sigma based transmitters for SDR application, due to their flexibility and reprogrammability. Different techniques have been proposed to address this issue. In one approach, a polar quantizer, instead of a conventional bi-level quantizer, is used in the delta-sigma modulator. Therefore, while the envelope of the PA driving signal is constant as desired, the magnitude of quantization noise can be decreased considerably without losing any signal quality. In this technique, the signal is able to keep its pulse-like shape, which is ideal for highly efficient switching-mode PAs. The ideas have been proven through simulation and measurement. Using these techniques, the overall efficiency is comparable with conventional transmitters with no need for the use of a linearizer.

Integrated Circuit Design – Microwave and Millimeter Wave

The growing demand for high-performance and low-cost integrated systems requires a great deal of research on integrated circuits, especially for the microwave subsystems. One of the important parts of wireless systems is the RF PA, which has a large impact on the performance of the wireless transmitters. In this research project, new structures and architectures are investigated, so that higher efficiency and better linearity specifications for the power amplifiers (PAs) can be achieved.

GaN MMIC PAs: The first part of this project is the design of wideband GaN (gallium nitride) MMIC (monolithic microwave integrated circuit) PAs for wireless communication applications. MMICs are of great interest in RF/microwave applications, due to their smaller size compared to that of hybrid circuits. Among the existing microwave device technologies, GaN is particularly suitable for MMIC PA applications, due to its superior performances over other technologies, such as gallium arsenide (GaAs) and silicon, which provides potential in the design of high-power, high-efficiency and broadband PAs. Switching-mode PAs rely on specific and precise multi-harmonic impedance terminations, such as short and open circuits. These PAs normally exhibit narrowband frequency performances of less than 10%, making switching-mode PAs less appealing for broadband applications. On the other hand, linear mode amplifiers, such as classes A, AB, and B, are less efficient than switching-mode PAs. Nevertheless, class-B PAs can theoretically achieve peak efficiencies as high as 78%. The bandwidth of conventional class-B PAs are also limited, due to the difficulty in the realization of their low impedance harmonic load terminations over wide bandwidths. A recently proposed linear class-J mode of operation has shown theoretical efficiencies as high as those of class-B PAs. However, since class-J PAs do not require harmonic resonators, there is potential for increasing PA bandwidth, with respect to other linear amplifiers, in order to achieve maximum efficiency.

In this work, a theoretical design procedure for an integrated class-J PA in 800 nm GaN technology with a 27 dBm output power at 2.5 GHz is proposed; and, the dependencies of the PA efficiency, optimal resistance and transistor width on the losses of an integrated inductor used in the output matching network are studied. The proposed design procedure has been verified by simulation of the designed class-J PA, and the measurement results show good agreement with the simulated ones. The bandwidth of the fabricated class-J amplifier was also compared with that of class-B PA, and an equal PA efficiency of greater than 40% in the integrated circuits was obtained. Measurement results show that the class-J PA is capable of achieving a fractional bandwidth of 33% in contrast to the 16% for the class-B PA, indicating that the bandwidth of the class-J amplifier is two times larger than that of the class-B PA. This makes the class-J PA a good candidate to replace the class-B and class-AB amplifiers recently used in base stations and other wireless communications systems that utilize broadband signals, such as WiMax and WCDMA. The next step is the use of a class-J amplifier in the Doherty PA structure and replacement of the conventional combiner circuit with a broadband one. The implementation of a GaN MMIC Doherty amplifier should allow the broadband amplifier to work very efficiently at 6 dB back-off power, which is suitable for high peak-to-average signals, such as WiMax and WCDMA.

CMOS MM-Wave PAs: The second thrust of this research direction is the development of architectures and design techniques for mm-wave CMOS (complementary metal oxide semiconductors) PAs. The 60 GHz unlicensed band is considered first for short-range, high data rate wireless personal area networks (WPANs). The large bandwidth available at this frequency band allows for multi-gigabit data rates. CMOS technology is the best option for digital circuits, but its performance for the microwave and mm-wave frequencies is less than expected and desired. To integrate all of the system parts on a single chip, microwave and mm-wave circuits should be implemented on CMOS technology. However, 60 GHz CMOS PAs have low efficiencies, particularly for signals with the high peak-to-average power ratios (PAPRs) specified by the standards. It has been well established that the Doherty architecture solves this problem at lower frequencies; however, at the 60 GHz band, Doherty architecture does not present high efficiency, due to losses in the output combining network.

We have proposed a new architecture and design methodology for the Doherty PA with a simpler combining network. The proposed architecture is also capable of working in a larger bandwidth than that of the conventional Doherty amplifier. The architecture was verified by a discrete design in the 2.2 GHz centre frequency with 25% of the fractional bandwidth. Moreover, a class-C peaking amplifier, which is the most challenging component in the Doherty architecture, was fabricated based on the proposed design methodology and tested using 65 nm CMOS technology. The test results have shown that the design goals are met using the proposed technique. In the future, the complete 60 GHz PA will be implemented using the proposed Doherty architecture in CMOS technology.

The activities carried out within this project of integrated GaN MMIC and CMOS PAs have been performed in close collaboration with Canadian Microsystem Corporation (CMC), who provided the design kit and measurement setups, technical support and fabrication of the chips.

4. OBJECTIVES FOR THE NEXT YEAR

The objectives for the coming year are in line with the research directions in the proposed research program of the Alberta Innovates Technology Futures (AITF) professorship proposal, covering April 2011 to March 2016. The overall long-term objective is the investigation of the scientific and technical problems related to software reconfigurable radio technology suitable for broadband and ultra-wideband communications, and multi-standard and multimode handsets and base stations. This objective is divided into objectives specific to the research tracks, as listed in the following subsections.

Green SDR Transceivers

This research thrust focuses on the design of intelligent software-defined radio (SDR) transceivers suitable for concurrent multi-standard and multi-carrier applications. As a continuation of past achievements in the modeling and design of switching-mode power amplifiers (SMPAs) and radio systems, new design approaches and methodologies will be investigated, in order to reach better power efficiency for multi-standard and multi-carrier signals. New all-digital architectures will be proposed and implemented to ensure the flexibility and ease of the reconfigurability of the entire RF front-end. Signal processing techniques, such as signal decomposition, noise shaping, noise reduction, linearization and equalization, will be investigated; and, new approaches and better practices will be proposed to significantly lower the energy consumption of the transmitter, while maintaining good quality of the signal at the antenna.

MIMO Radio Systems

To increase the spectrum efficiency and channel capacity in wireless transmissions, new architectures based on MIMO (multiple input, multiple output) systems will be proposed. These MIMO transceiver architectures will overcome the performance degradation in conventional MIMO systems, which are caused by the combined effect of the component's impairment and the cross-coupling between the transmitter and receiver branches. This research thrust aims at the proposal of innovative system architectures and signal processing algorithms that shield MIMO radios from these analog circuit impairments and from problems triggered by the proximity of crosstalk between adjacent branches in MIMO radios.

UWB/MM-Wave Radios

To increase the channel capacity, the signal bandwidth must be increased. This research thrust focuses on the design of ultra-wideband (UWB) transceivers that are able to transmit signals at a speed of gigabits per second. New transceiver architectures and design approaches will be proposed to implement transceivers at the unlicensed mm-wave frequency band around 60 GHz for the IEEE 802.15c3 wireless personal area network (WPAN) standard. These architectures and approaches aim at reducing the effect of the pronounced impairments at this frequency range. Special attention will be given to the amplification topology, where a new multimode Doherty topology will be proposed and implemented, in order to maintain high power efficiency, good signal quality and low signal processing complexity.

DSP for Wireless Communications

The linearization of PAs and transmitters under wideband (100 MHz and more) drive signals is being pursued. The main limitation observed so far is largely due to the wide bandwidth of the observation path. Accordingly, particular interest will be given to sub-band processing techniques, in order to broaden the observation window, while maintaining an acceptable dynamic range and signal quality, with the bandwidth limitation and the availability of a smart multipurpose wireless platform. Conventional linearization techniques, however, will not be efficient or practical for use with concurrent dual-band transmitters, due to either impractical sampling rate requirements of the analog-to-digital and digital-to-analog converters (ADCs and DACs, respectively) required for these conventional digital predistortion (DPD) techniques or neglect of the cross-modulation effects between the multiple frequency bands. A new multi-band linearization architecture will be developed that features distortion compensation for the concurrent multiband transmitter.

Another research topic in the digital signal processing (DSP) track is the design and development of energy efficient transmitter architecture for carrier aggregation (CA) in 4G (fourth generation) LTE-Advanced wireless technology. For the sake of high data rates, the LTE-Advanced standard considers the possibility of having signal transmissions up to the 100 MHz bandwidth. In fact, the component carriers (CCs) of the signal in both up-link and down-link are limited to 20 MHz; however, CA of multiple CCs (up to a maximum of five) has been introduced to broaden the overall signal bandwidth to up to 100 MHz. When it comes to the realization of CA techniques, the transmitter architecture is of great importance. The main difficulties are in the realization and implementation of transmitters supporting an inter-band CA technique. The main objective of this project is an energy efficient solution for implementation of inter-band CA for LTE-Advanced systems.

Adaptive and Tuneable Receivers

lThe main challenge in offering an effective solution for the design of adaptive and tuneable receivers is the implementation of a low-cost ultra-wideband (UWB) receiver with minimum impairments in the down-converter. A typical receiver chain calls for the use of a down-converter targeted for a specific RF band and an analog-to-digital converter to reconstruct the transmitted signal. If the down-converter is replaced with a track-and-hold component, the signal may be directly digitized from the RF signal. This technique, called subsampling, allows for a receiver to target different RF signals by changing the clock frequency of the track-and-hold circuit. Initial simulations and measurements have proven the capability of such architecture in receiving different signals. Application to multi-band and multi-standard wireless communications and concurrent multi-band predistortion will be considered in the coming years. A proof-of-concept prototype for a subsampling receiver that is able to down-convert signals with carrier frequencies between 500 MHz and 4 GHz will be designed and tested.

A second architecture for adaptive receivers consists of using a passive multi-port network with circuit post-calibration to design a UWB receiver. A proof-of-concept design was assembled to work on a frequency band from 2 GHz to 12 GHz. Calibration algorithms able to compensate for the power detector static nonlinearity allowed a signal-to-noise ratio (SNR) of about 30 dB for the received signals of a bandwidth lower than 5 MHz. Increasing the signal bandwidth results in deterioration of the signal quality (SNR degrades by more than 10 dB for a signal with a 20 MHz bandwidth), due to the frequency response of the receiver and the memory effects of the diodes. Dynamic linearization and calibration algorithms able to compensate for the frequency response and the dynamic will be investigated to enable UWB reception capabilities in the six-port receiver. A new calibration and linearization algorithm that can be achieved in one step without having to separately measure each of the components of the six-port receiver will be considered. Using a training sequence in the header of each frame is believed to allow for one-step calibration and linearization. Testing with 4G standards, such as WiMAX and LTE-Advanced, will be carried out to investigate the possibility of using the current frame header as a training sequence or to propose alternatives.

5. RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

FACULTY		
Name	Role / Topic	Awards / Special Info
Dr. Fadhel Ghannouchi	Team Leader, Director of iRadio Lab, AITF Professor in Intelligent RF Radio Technology and Canada Research Chair (Tier 1). 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 was selected as IEEE-MTT-S' Distinguished Microwave Lecturer for the three-year period of 2009-2011. Dr. Ghannouchi was elected as a Fellow of the Royal Society of Canada (Feb. 2011). Dr. Ghannouchi is a member of the International Advisory Board of the Gigahertz Research Centre, Sweden (2007-present).
Dr. Mohamed Helaoui	AITF associate, assistant professor Research interests are in the areas of RF and wireless communications, signal processing for ultra-wideband receivers.	Dr. Helaoui received a start-up research grant from the Department of Electrical and Computer Engineering and the Schulich School of Engineering.

Dr. M. Fattouche	Professor Research interests include wireless location and communication systems	Dr. Fattouche is associated with iRadio Lab
Dr. L. Belostotski	Assistant professor Research interests include CMOS RFIC transceivers design	Dr. Belostotski is associated with iRadio Lab

VISITING PROFESSOR / RESEARCHERS		
Name	Role / Topic	Awards / Special Info
Dr. F. Falcone	Professor, University of Navarra , Spain	
Jose Ramon Garcia Oya	Visiting Graduate Student	

VISITING SPEAKERS		
Name	Topic	Special Info
Dr. Serioja Ouidiu Tatu, Professor, Université du Québec, INRS	60 GHz UWB multiport transceivers	
Dr. Diuxian Liu, IBM T.J. Watson Research Center, New York	Aperture-coupled patch antenna designs for 60 GHz package applications	
Dr. Zhenghe Feng, Professor, Department of Electronic Engineering, Tsinghua University	Antenna research at Tsinghua University	
Dr. Cevdet Akyel, Professor, École Polytechnique de Montréal	Microwave applications in fields other than communications	
Dr. Renato Negra, UMIC Research Centre, RWTH Aachen University	Flexible digital-centric wireless transmitters	

RESEARCH ASSOCIATES / ASSISTANTS		
Name	Role / Topic	Awards / Special Info
Andrew Kwan	Research associate	

POSTDOCTORAL FELLOWS		
Name	Role / Topic	Awards / Special Info
Dr. A. S. Bassam	DSP for wireless transceivers	Graduated from University of Calgary
Dr. Donglin Wang	Wireless location and channel modeling	Graduated from University of Calgary

Dr. Wenhua Chen	Dual-band transceivers design	Graduated from Tsinghua University, China
Dr. Mohammad Hashmi	Waveform engineering	Graduated from Cardiff University, UK

PH.D. STUDENTS		
Name	Role / Topic	Awards / Special Info
Jose R. Garcia Oya	Novel digital pre-distortion (DPD) linearizer for multi-band transmitter	Visiting Ph.D. Student, University of Seville, Seville, Spain
Mr. Youjiang Liu	Multi-band linearization	Visiting Ph.D. student, Tsinghua University, China
Imen Mrissa	LTE transceiver design	Visiting Ph.D. student, INRS, Université du Québec
Maryam Jouzdani	Pulse load modulation technique	University of Calgary
Ahmet Hayrettin Yuzer	Thermal memory effects modeling	Visiting Ph.D. student, Middle East Technical University (METU), Turkey, Turkish Government Award, supervised by Drs. F.M. Ghannouchi and D. Simsek
Mohammadhassan Akbarpour	60 GHZ CMOS PA design	ICT – Alberta Innovates Award, co-supervised by Drs. F.M. Ghannouchi and M. Helaoui
Pouya Aflaki	GaN Based PA design with application to polar transmitters	University Award, supervised by Dr. F.M. Ghannouchi
Walid Saber El-Deeb	Design and implementation of RF waveform measurement system	Holds an international graduate scholarship from the Egyptian Government, supervised by Dr. F.M. Ghannouchi
Afef Hargel	Memory polynomial based models for RF transmitters linearization	Associate, Faculté des Sciences, Université de Tunis, Tunisia, co-supervised by Drs. A. Gharsallah and F.M. Ghannouchi
Mohammed Mojtaba Ebrahimi	Multi-band transceiver design	Co-supervised by Drs. M. Helaoui and F.M. Ghannouchi
Karun Rawat	Multi-standard SDR transmitters	University Award, supervised by Dr. F.M. Ghannouchi
Saeed Rezaei Nazifi	Generic analog linearization systems	University Award, co-supervised by Drs. F.M. Ghannouchi and L. Belostotski
Mehdi Vejdani Amiri	MIMO radio systems	University Award, co-supervised by Drs. M. Helaoui and F.M. Ghannouchi
Fahmi Elsayed	All-digital transmitter	Co-supervised by Drs. F.M. Ghannouchi and M. Helaoui
Dhikra Saffar	MIMO behavioural modeling	Associate, Faculté des Sciences, Université de Tunis, Tunisia, co-supervised by Drs. A. Gharsallah and F.M. Ghannouchi
Saeed Ghamari	Six-port receiver	University Award, co-supervised by Drs. M. Helaoui and F.M. Ghannouchi.
Ramzi Darraji	Multimode amplifiers	ICT – Alberta Innovates Award, supervised by Dr. F. M. Ghannouchi
Mayada Younes	Memory effect analysis and modeling	University Award, supervised by Dr. F.M. Ghannouchi
Meenakshi Rawat	Neural network modeling of radio systems	University Award, supervised by Dr. F.M. Ghannouchi

M.SC. CANDIDATES		
Name	Role / Topic	Awards / Special Info
Anis M. Messaoud	Subsampling receivers	Visiting M.Sc. student, University of Carthage, Tunisia
Mr. Jiannan Li	Behaviour modeling	Visiting M.Sc. student, Tsinghua University, China
Abul Hassam	SDR receivers	University Award, supervised by Dr. M. Helaoui
Suhas Illath Veetil	Not yet defined	Supervised by Dr. M. Helaoui
Sharif Rahman	Not yet defined	Supervised by Dr. F.M. Ghannouchi
Levent Erdogan	Use of microwave energy in tar sands applications	Associate, École Polytechnique de Montréal, co-supervised by Drs. C. Akyel and F.M. Ghannouchi
Shubhrajit Bhattacharjee	RF transceivers design	University Award, supervised by Drs. F.M. Ghannouchi and H. Leung

OTHER TEAM MEMBERS (ASSOCIATES, UNDERGRADUATE STUDENTS, SUPPORT STAFF)	
Name	Role / Topic
Andrew Kwan	Lab Manager
Christopher Simon	Technical support
Tibor Bata	Technical support to students for printed circuit board (PCB) fabrication and instrumentation
Ivana D’Adamo	Administrative support to Dr. Ghannouchi and the iRadio Lab team

6. COLLABORATIONS

NATIONAL COLLABORATIONS	
Participants	Nature of Collaboration
École Polytechnique de Montréal: Dr. K. Wu Dr. R. Malhame Dr. C. Akyel	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, one graduate student from École Polytechnique de Montréal is currently supervised by Dr. F.M. Ghannouchi.
Université de Québec: Dr. A. Kouki	The ongoing theme of collaboration is related to LINC-based amplifiers and GaN transistors modeling.
INTERNATIONAL COLLABORATIONS	
Participants	Nature of Collaboration
Aachen University, Germany: Dr. R. Negra	The ongoing collaboration is related to the modeling of GaN transistors and the design of switching-mode PAs and transmitters.
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 DPD technology using DSP/FPGA modules and the design of multistandard receivers using RF subsampling techniques. Several joint papers have been published that report the results to date. Dr. F.M. Ghannouchi is co-supervising the work of three Ph.D. candidates.

Université de Bordeaux, France: Dr. E. Kerhervé Y. Deval	Collaboration with the IXL Laboratory at the Université de Bordeaux to study, analyze and assess the suitability of integrated multiband RF power amplifiers.
Ningbo University, 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.
Tsinghua University, Beijing, China: Prof. Z. H. Feng	Collaboration was initiated this year. Ongoing research activities are related to the design of dual-band Doherty PAs.
Amirkabir University, Iran: Prof. A. Mohammadi	Collaboration was initiated this year. Ongoing research activities on six-port receivers and MIMO wireless systems.
INDUSTRIAL COLLABORATIONS	
Participants	Nature of Collaboration
Canadian Space Agency, Canada: G. Brassard T. Pellerin	In the frame of an NSERC Collaborative Research and Development (CRD) grant, the objective of this collaboration is the development of GaN-based innovative Doherty PAs intended for the Canadian Space Agency's Quicksat program.
Focus Microwaves, Canada: Dr. C. Tsironis Dr. Z. Ouardirhi	Focus Microwaves is sponsoring an ongoing NSERC Collaborative Research and Development (CRD) grant 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 PAs for satellite and avionic applications.
Ericsson, Canada: P. Olanders, B. Morris	The collaboration with Ericsson was initiated last year. Ericsson is currently supporting an NSERC strategic grant application related to the development of multimode transmitters.
Powerwave Technologies, USA: Dr. N. Braithwaite	The collaboration with Powerwave Technologies was initiated last year and is aimed at the modeling and linearization of Powerwave's commercial PAs.
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 PAs.
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.
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 with free software licences for special toolboxes needed to build the SDR platform in the context of SDR challenge 2008.
Agilent Technologies, USA	The collaboration is related to the wideband characterization and modeling of wireless transmitters

7. GRADUATES

POSTDOCTORAL FELLOWS			
Name	Degree	Research Topic	Current Position
Walid S. El Deeb	PDF	Nonlinear network analyzers	Assistant Professor, Zagazig University, Egypt
Aidin S. Bassam	PDF		Senior Engineer, Powerwave Technologies, CA

PH.D. CANDIDATES			
Name	Degree	Research Topic	Current Position
Walid S. El Deeb	Ph.D.	Nonlinear network analyzers	Assistant Professor, Zagazig University, Egypt
Pouya M. Aflaki	Ph.D.	Switching-mode amplifiers	PDF at ETS, Université du Québec, Montréal
Aidin S. Bassam	Ph.D.	Linearization of MIMO radios	Senior Engineer, Powerwave Technologies, CA
Chokri Jebali	Ph.D.	Behaviour modeling of wireless transmitters	Assistant Professor, University of Monasitr, Tunisia

M.Sc. CANDIDATES			
Name	Degree	Research Topic	Current Position
Shubhrajit Bhattacharjee	M.Sc.	Wireless channel modeling	Co-supervised by Drs. H. Leung and F.M. Ghannouchi
Mayada Younes	M.Sc.	Behavior modeling of wireless transmitters	Supervised by Dr. F.M. Ghannouchi

8. INTELLECTUAL PROPERTY

Patents and Patent Applications:

1. T. Liu, S. Boumaiza and F. M. Ghannouchi, "Nonlinear behavior models and methods for use thereof in wireless radio systems," US Patent 8,078,561, 13 December 2011.
2. F. M. Ghannouchi, S. A. Bassam, M. Helaoui and A. Kwan, "Digital Multi-band Predistortion Linearizer with Nonlinear Subsampling Algorithm in the Feedback Loop," US Patent Application 13/274/290, filed 14 October 2011.
3. F. M. Ghannouchi and R. Darraji, "Digital Doherty Transmitter," US Patent Application 13/105/852, filed 11 May 2011.
4. F. M. Ghannouchi, S. Bensmida, M. Hashmi and M. Helaoui, "Passive source and load-pull architecture for high reflection factor synthesis," US Patent Application 13/097/303, filed 29 April 2011.

Refereed Journal Publications:

1. M. Younes and F. M. Ghannouchi, "An Accurate Predistorter Based on a Feedforward Hammerstein Structure," IEEE Transactions on Broadcasting, 2012, Accepted.
2. D. Wang, R. He, J. Han, M. Fattouche and F. M. Ghannouchi, "Sensor Network Based Oilwell Health Monitoring and Intelligent Control," IEEE Sensors Journal, 2011 Accepted.

3. D. Wang and F. M. Ghannouchi, "Handset Based Positioning System For Injured Fireman Rescue in Wildfire Fighting," IEEE Systems Journal, 2011 Accepted.
4. D. Wang, M. Fattouche and F. M. Ghannouchi, "Geometry-based Doppler analysis for GPS receivers," Wireless Personal Communications, 2011 Accepted.
5. D. Wang, M. Fattouche and F. M. Ghannouchi, "Fundamental Limit of OFDM Range Estimation in a Separable Multipath Environment," Circuits, Systems, and Signal Processing, 2011 Accepted.
6. D. Wang, M. Fattouche and F. M. Ghannouchi, "Efficient Spectrum Allocation and TOA-based Localization in Cognitive Networks," Wireless Personal Communications, 2011 Accepted.
7. M. Rawat, F. M. Ghannouchi and K. Rawat, "Three-Layered Biased Memory Polynomial for Modeling and Predistortion of Transmitters with Memory," IEEE Transactions on Circuits and Systems I: Regular Papers, 2012 Accepted.
8. M. Rawat and F. M. Ghannouchi, "A Mutual Distortion and Impairment Compensator for Wideband Direct Conversion Transmitters using Neural Networks," IEEE Transactions on Broadcasting, 2011 Accepted.
9. K. Rawat, M. Rawat, M. S. Hashmi and F. M. Ghannouchi, "Dual-Band Branch-Line Hybrid With Distinct Power Division Ratio Over The Two Bands," Wiley International Journal of RF and Microwave Computer-Aided Engineering, 2012 Accepted.
10. K. Rawat and F. M. Ghannouchi, "Design Methodology for Dual-Band Doherty Power Amplifier with Performance Enhancement using Dual-Band Offset lines," IEEE Transactions on Industrial Electronics, 2011 .
11. A. Kwan, F. M. Ghannouchi, O. Hammi, M. Helaoui and M. R. Smith, "LUT-based Digital Predistorter Implementation for FPGAs using LTE signals with 60 MHz Bandwidth," IET Science, Measurement & Technology, 2011 Accepted.
12. C. Jebali, N. Boulejfen, M. Rawat, A. Gharsallah and F. M. Ghannouchi, "Modeling of Wideband RF Power Amplifiers Using Zernike Polynomials," Wiley International Journal of RF and Microwave Computer-Aided Engineering, 2011 Accepted.
13. C. Jebali, N. Boulejfen, A. Gharsallah and F. M. Ghannouchi, "Effects of Signal PDF on the Identification of Behavioral Polynomial Models for Multicarrier RF Power Amplifiers," Analog Integrated Circuits and Signal Processing, 2011 Accepted.
14. C. Jebali, N. Boulejfen, A. Gharsallah and F. M. Ghannouchi, "Numerical Analysis Methods for RF Power Amplifier Characterization," International Journal of Communication Networks and Information Security, Accepted.
15. B. Georgescu and F. M. Ghannouchi, "Comparative Analysis of Tunable Q-enhancement Filter Cell Topologies in a 2.4 GHz LNA," Circuits, Systems, and Signal Processing, 2012 Accepted.
16. R. Darraji, F. M. Ghannouchi and O. Hammi, "Generic Load-Pull Based Design Methodology for Performance Optimization of Energy-Efficient Doherty Amplifiers," IET Science, Measurement & Technology, 2011 Accepted.
17. N. Boulejfen, F. Elsayed, M. Helaoui, L. DeVocht and F. M. Ghannouchi, "Efficiency Enhancement of Sigma–Delta Modulator Based Transmitters Using Multi-Level Quantizers," Journal of Signal Processing Systems, 2011
18. S. A. Bassam, A. Kwan, W. Chen, M. Helaoui and F. M. Ghannouchi, "Subsampling Feedback Loop Applicable to Concurrent Dual-Band Linearization Architecture," IEEE Transactions on Microwave Theory and Techniques, 2012 Accepted.
19. W. S. El-Deeb, M. S. Hashmi, N. Boulejfen and F. M. Ghannouchi, "Systematic Calibration of Two-Port Net-Work Analyzer for Measurement and Engineering of Waveforms at Radio Frequency," Progress In Electromagnetics Research C, Vol. 28, pp. 209-222, April 2012.
20. K. Rawat, M. S. Hashmi and F. M. Ghannouchi, "Double the Band and Optimize," IEEE Microwave Magazine, Vol. 13: Issue 2, pp. 69-82, March-April 2012.
21. M. M. Ebrahimi, S. A. Bassam, M. Helaoui and F. M. Ghannouchi, "Applying memory polynomial model to linearize wideband multi-bit delta-sigma based transmitters," AEU - International Journal of Electronics and Communications, pp. 1-5, 16 March 2012 2012.

22. M. Rawat and F. M. Ghannouchi, "Distributive spatiotemporal Neural Network for Nonlinear Dynamic Transmitter Modeling and Adaptive Digital Predistortion " IEEE Transactions on Instrumentation & Measurement, Vol. 61: Issue 3, pp. 595-608, March 2012.
23. W. Chen, A. Kwan and F. M. Ghannouchi, "Hybrid envelope tracking for efficiency enhancement in concurrent dual-band PAs," Microwave and Optical Technology Letters, Vol. 54: Issue 3, pp. 662-664, March 2012.
24. K. Rawat, M. S. Hashmi and F. M. Ghannouchi, "Dual-Band RF Circuits and Components for Multi-standard Software Defined Radios," IEEE Circuit and System Magazine, Vol. 12: Issue 1, pp. 12-32, February 2012.
25. S. Tiwari, D. Wang, M. Fattouche and F. Ghannouchi, "A Hybrid RSS/TOA Method for 3D Positioning In an Indoor Environment," ISRN Signal Processing, Vol. 2012, Article ID 503707, pp. 1-9, 2012.
26. M. Rawat, K. Rawat and F. M. Ghannouchi, "Recent advances on signal processing solutions for distortion mitigation due to power amplifier and non-ideality of transmitter system," Recent Patents on Signal Processing, Vol. 1: Issue 2, pp. 135-142, December 2011.
27. A. Mohammadi and F. M. Ghannouchi, "Single RF Front-End MIMO Transceivers," IEEE Communications Magazine, Vol. 49: Issue 12, pp. 104-109, December 2011.
28. A. Bassam, W. H. Chen, M. Helaoui, F. M. Ghannouchi and Z. H. Feng, "Linearization of Concurrent Dual-Band Power Amplifier Based on 2D-DPD Technique," IEEE Microwave and Wireless Components Letters, Vol. 21: Issue 12, pp. 685-687, December 2011.
29. D. Saffar, N. Boulejfen, F. M. Ghannouchi, A. Gharsallah and M. Helaoui, "Behavioral Modeling of MIMO Nonlinear Systems with Multivariable Polynomials," IEEE Transaction on Microwave Theory and Techniques, Vol. 59: Issue 11, pp. 2994-3003, November 2011.
30. K. Rawat and F. M. Ghannouchi, "Dual-band matching technique based on dual-characteristic impedance transformers for dual-band power amplifiers design," IET Microwaves, Antennas & Propagation, Vol. 5: Issue 14, pp. 1720-1729, November 2011.
31. R. Darraji and F. M. Ghannouchi, "Digital Doherty Amplifier with Enhanced Efficiency and Extended Range," IEEE Transactions on Microwave Theory and Techniques, Vol. 59: Issue 11, pp. 2898-2909, November 2011.
32. W. H. Chen, S. A. Bassam, X. Li, Y. Liu, M. Helaoui, K. Rawat, F. M. Ghannouchi and Z. Feng, "Design and Linearization of Concurrent Dual-Band Doherty Power Amplifier With Frequency-Dependent Power Ranges," IEEE Transactions on Microwave Theory and Techniques, Vol. 59: Issue 10, pp. 2537-2546, October 2011.
33. A. Bassam, M. Helaoui and F. M. Ghannouchi, "2-D Digital Predistortion (2-D-DPD) Architecture for Concurrent Dual-Band Transmitters," IEEE Transactions on Microwave Theory and Techniques, Vol. 59: Issue 10, pp. 2547-2553, October 2011.
34. M. Hashmi, F. M. Ghannouchi, P. J. Tasker and K. Rawat, "Highly Reflective Load-Pull," IEEE Microwave Magazine, Vol. 12: Issue 4, pp. 96-107, June 2011.
35. F. M. Ghannouchi, F. Taringou, A. Kwan, O. Hammi and R. Malhame, "Identification of true-static predistorter using a sine wave and accurate quantification of memory effects in broadband wireless transmitters " IET Communications, Vol. 5: Issue 9, pp. 1268-1274, June 2011.
36. W. S. El-Deeb, M. S. Hashmi, N. Boulejfen and F. M. Ghannouchi, "Small-Signal, Complex Distortion and Waveform Measurement System for Multi-Port Microwave Devices," IEEE Instrumentation & Measurement Magazine, Vol. 14: Issue 3, pp. 28-33, June 2011.
37. K. Rawat, F. M. Ghannouchi, M. Rawat and M. S. Hashmi, "Analysis of Frequency-Selective Impedance Loading of Transmission Lines for Dual-Band Couplers.," Wiley International Journal of RF and Microwave Computer-Aided Engineering, Vol. 21: Issue 3, pp. 325-335, May 2011.
38. R. Darraji, F. M. Ghannouchi and O. Hammi, "A Dual-Input Digitally Driven Doherty Amplifier Architecture for Performance Enhancement of Doherty Transmitters," IEEE Transactions on Microwave Theory and Techniques, Vol. 59: Issue 5, pp. 1284-1293, May 2011.
39. M. Lari, A. Bassam, A. Mohammadi and F. M. Ghannouchi, "Time-multiplexed single front-end multiple-input multiple-output receivers with preserved diversity gain," IET Communications, Vol. 5: Issue 6, pp. 789-796, April 2011.

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1. K. Rawat, M. S. Hashmi, F. Falcone and F. M. Ghannouchi, "Dual-Band Phase Offset Line with Required Transmission Phases at Two Operational Frequencies," in 2012 IEEE MTT-S International Microwave Symposium Digest (IMS'2012), Montreal, QC, 17-22 June 2012 Accepted.
2. J. G. Oya, A. Kwan, S. A. Bassam, F. Munoz and F. M. Ghannouchi, "Optimization of Subsampling Dual Band Receivers Design in Nonlinear Systems," in 2012 IEEE MTT-S International Microwave Symposium Digest (IMS'2012), Montreal, QC, 17-22 June 2012 Accepted.
3. A. Hasan, M. Helaoui and F. M. Ghannouchi, "Dynamic Linearization of Diodes for High Speed and Peak Power Detection Applications," in 2012 IEEE MTT-S International Microwave Symposium Digest (IMS'2012), Montreal, QC, 17-22 June 2012 Accepted.
4. K. Rawat and F. M. Ghannouchi, "Load-Pull Assisted CAD design of Inverted Doherty Power Amplifier Without Quarter-Wave Transformer," in 25th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2012), Montreal, QC, 29 April - 2 May 2012 Accepted.
5. M. M. Ebrahimi, M. Healoui and F. M. Ghannouchi, "Improving Coding Efficiency by compromising linearity in delta-sigma based transmitters " in 2012 IEEE Radio and Wireless Symposium (RWS), Santa Clara, CA, USA, pp. 411-414, 15-19 January 2012.
6. A. Kwan, A. Bassam and F. Ghannouchi, "Sub-sampling Technique for Spectrum Sensing in Cognitive Radio Systems," in IEEE Radio and Wireless Symposium (RWS'2012), Santa Clara, CA, USA, 15-19 January 2012 Accepted.
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9. F. M. Ghannouchi, "Extrinsic Extraction Procedure for A Small-Signal Gan-Hemt Model," in 23rd International Conference on Microelectronics (ICM'2011), Hammamet, Tunisia, 19-22 December 2011 Accepted.
10. F. M. Ghannouchi, "A Genetic Neural Network Modeling of GaN HEMTs for RF Power Amplifiers Design," in 23rd International Conference on Microelectronics (ICM'2011), Hammamet, Tunisia, 19-22 December 2011 Accepted.
11. R. Darraji and F. Ghannouchi, "Digital Doherty Amplifier with Complex Gain Compensation Apparatus," in Asia Pacific Microwave Conference 2011 (APMC'2011), Melbourne, Australia, 5-8 December 2011 Accepted.
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17. F. M. Ghannouchi and K. Rawat, "Doherty Power Amplifiers in Software Radio Systems," in 2011 URSI General Assembly and Scientific Symposium (GASS'2011), Istanbul, Turkey, 13-20 August 2011.

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20. V. Torres, M. Rawat, F. Esparza, K. Rawat, R. Darraji, F. Ghannouchi and F. Falcone, "Analysis of performance modeling of Wireless Systems in complex Indoor Scenarios," in 2011 IEEE AP-S International Symposium on Antennas and Propagation and 2011 USNC/URSI National Radio Science Meeting (APS'2011), Spokane, WA, USA, 3-8 July 2011.
21. M. Rawat, K. Rawat, F. Esparza, R. Darraji, V. Torres, F. Falcone and F. M. Ghannouchi, "Directional Beam Forming for Smart Antenna with Ray-Launching and Neural Networks," in 2011 IEEE AP-S International Symposium on Antennas and Propagation and 2011 URSI National Radio Science Meeting (APS'2011), Spokane, WA, USA, 3-8 July 2011.
22. S. R. Nazifi, M. S. Hashmi, B. Dehlaghi and F. Ghannouchi, "Systematic Methodology to Design Analog Predistortion Linearizer for Dual Inflection Power Amplifiers," in 2011 IEEE MTT-S International Microwave Symposium Digest (IMS'2011), Baltimore, MD, USA, pp. 1-4, 5-10 June 2011.
23. K. Rawat and F. Ghannouchi, "C-Band Microstrip Based Band-Pass Filter with Design Oriented Transmission Zeros Allocation," in 24th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2011), Niagara Falls, ON, Canada, pp. 1179-1181, 8-11 May 2011.
24. W. S. El-Deeb, M. S. Hashmi, N. Boulejfen and F. M. Ghannouchi, "On-line waveform monitoring system for the design and characterization of MIMO RF PAs," in 24th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2011), Niagara Falls, ON, Canada, pp. 1024-1027, 8-11 May 2011.
25. R. Darraji and F. Ghannouchi, "High Efficiency Harmonically-Tuned GaN Power amplifier for 4G applications," in 24th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2011), Niagara Falls, ON, Canada, pp. 1264-1267, 8-11 May 2011.
26. S. Bhattacharjee, K. Rawat, M. Rawat, D. Wang, M. Helaoui, H. Leung and F. Ghannouchi, "Joint Evaluation and Mitigation of RF Impairments and Nonlinear Distortion in WiMAX Transceiver under Nakagami-m Fading Channel," in 24th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2011), Niagara Falls, ON, Canada, pp. 926-929, 8-11 May 2011.

Books and Chapters:

1. A. Mohammadi and F. M. Ghannouchi, RF Transceiver Design for MIMO Wireless Communications. Springer 2012.

Special/Invited Presentations:

1. Professor F. M. Ghannouchi gave an invited talk entitled “Green Electronics and Wireless Technology" at The Engineering Associates Program meeting, Calgary , CA , January 20, 2012.
2. Professor F. M. Ghannouchi as a Distinguish Microwave Lecturer gave an invited talk entitled “Digital Dual-band Doherty amplifiers “at The IEEE Radio Wireless Symposium, Santa Clara, CA , January 16, 2012.
3. Professor F. M. Ghannouchi as a Distinguish Microwave Lecturer gave an invited talk entitled " Advanced Amplifiers and transmitters for SDR applications” NXP Corporation, Caen France, December 16, 2011.
4. Professor F. M. Ghannouchi as a Distinguish Microwave Lecturer gave an invited talk entitled “RF/DSP Co-Designed Doherty amplifiers” " at IEEE Asia Pacific Microwave Conference, Melbourne, Australia, December 6, 2011.
5. Professor F. M. Ghannouchi as a Distinguish Microwave Lecturer gave an invited talk entitled “Software Radio Systems “at The Technical University of Sydney, Sydney Australia, December 2, 2011.

6. Professor F. M. Ghannouchi as a Distinguish Microwave Lecturer gave an invited talk entitled “Design of RF Front-ends for Software Radio Systems “at The University of Southern California, Veterbi School of Engineering, Los-Angeles, USA October 14, 2011.
7. Professor Ghannouchi gave a keynote talk on "Software Defined Transmitters for Wireless Applications" at 2011 Mediterranean Microwave conference held in Hammamet, Tunisia on September 9, 2011
8. Professor F. Ghannouchi gave an invited talk entitled "Doherty Power Amplifiers in Software Radio System" at The XXX General Assembly and Scientific Symposium of the International Union of Radio Science held in Istanbul, Turkey on August 19th, 2011
9. Professor F. Ghannouchi is giving an invited talk on "Multi-band Doherty Transmitters for Wireless Applications” at the workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC) will be held at the Vienna University of Technology, Vienna (Austria) on April 18th - 19th, 2011.

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 can be found at http://iradio.ucalgary.ca/seminars/lab_seminars .

10. OUTREACH

The community outreach activities of iRadio Lab included:

1. Saeed Rezaei from iRadio Lab was awarded the "Analog Device, Outstanding student design Award" at the IEEE International Solid-State Circuits Conference, San Francisco, February 22, 2012.

2. Saeed Rezaei from iRadio Lab was awarded the Teledyne DALSA Component Ware/CAD Award for his presentation "Broadband High-Efficiency Class-J MMIC Power Amplifier Design in 0.8um GaN Technology".

3. Dr. Fadhel Ghannouchi, as a Distinguished lecturer for IEEE, gave several presentations around the world, and attended or participated in various committees for conferences.

4. Dr. Fadhel Ghannouchi was a reviewer for various national and international granting agencies.

5. Dr. Fadhel Ghannouchi was a member of several international technical committees and editorial journal boards.

6. Dr. Fadhel Ghannouchi was a technical program committee member for several international conferences and symposiums.

7. Dr. Fadhel Ghannouchi was a technical legal expert in a USA court case.

8. Dr. Fadhel Ghannouchi was a participant in various university and industry information sessions and promotional events.

11. FINANCIAL REPORTS

AITF Revenues/Expenses

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

Funding Sources

The funding sources report lists all of our active funding sources. The provided spreadsheet for this purpose has been 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