Alberta Informatics Circle of Research Inc

iRadio Laboratory Annual Report
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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.

iRadio Lab was founded in May 2005, and it is already staffed with more than twenty graduate students and talented researchers that have been 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 prototyping, is also being used by graduate students and researchers. The iRadio Lab 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 wireless communications industries 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-four refereed published and accepted journal papers, eighteen refereed conference papers, three US patent applications and the publication of a book. Twenty keynotes and invited talks were given by iRadio Lab researchers at international conferences and leading research institutions and universities. At the 3rd Smart Radio Challenge, which is an international competition organized yearly by the Wireless Innovation Forum, a team of five graduate students from iRadio Lab, mentored by Dr. F. Ghannouchi, won first place with a scholarship prize of $4,000, as well as Best Design with a scholarship prize of $2,000

During its fifth year, iRadio Lab was successful in securing substantial funding: $210K from the Natural Sciences and Engineering Research Council of Canada (NSERC) and $25K from industry. These monies supplement the $300K, $200K and $150K yearly averages provided by iCORE, 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 $77,500K from industry 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 iRadio Lab personnel directly affiliated with the University of Calgary currently includes two faculty members, two technical support staff, one administrative support staff, one lab manager, one research assistant, four postdoctoral fellows, one visiting scholar, and eighteen 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, Cree);

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

iii. Digital electronics, digital signal processing (DSP) and CAD software (Analog Devices, Altera, Xilinx, Agilent Technologies, Canadian Microelectronics 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 digital signal processing (DSP) and mixed signal technology, RF and microwave 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 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.

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.

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.

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 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 light of the initial main goals relevant to this project.

Microwave and Radio Frequency Devices, Circuits and Systems 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, 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 has been investigated. According to this study, a switching-mode PA designer is able to make the 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* 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 analytical-based model, two terms were added to the original drain current equation borrowed from LDMOS 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 transmitters for the emerging communication standards (third generation and beyond). The activities carried out within this project of multi-input digital Doherty PAs have been performed in close collaboration with the Canadian Space Agency (CSA), CMC and the University of Quebec.

In continuation of work done in previous years on the design of the highly efficient Doherty PAs, hardware improvement techniques and innovative design methodologies have been investigated to get the best efficiency performance out of the analog circuit. The focus of this study was the understanding of the effect of the offset line, which are commonly used at the output of the carrier and peaking amplifiers, on the overall performance of the Doherty PA. This resulted in the design of high-efficiency GaN based Doherty PA. In fact, power-added efficiencies of 52% and 61% have been measured at 7 dB output power back-off (OPBO) and full power drive, respectively, for a GaN based Doherty PA with a maximum output power of 20 watts. Along with the digital predistortion (DPD) technique, the Doherty amplifier prototype has successfully met the linearity requirements of the WiMAX (Worldwide Interoperability for Microwave Access) standard.

Further optimizations of the circuit were carried out by employing DSP-based performance enhancement techniques. In this context, a new dual-input digitally driven Doherty amplifier architecture was implanted in GaN technology. The efficiency enhancement was obtained through the implementation of a digital adaptive phase alignment mechanism to compensate for the power-dependent phase disparity between the output combining paths of the Doherty PA. A power-added efficiency of 57% was obtained on a dual-input digital Doherty PA prototype implemented in GaN technology.

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

Advanced Adaptive Digital Signal Processing Algorithms for Wireless Transceivers

The next generation of wireless transceivers enables researchers to utilize advanced adaptive signal processing techniques for performance improvement. This can be divided into three tracks: nonlinearity modeling and compensation, hardware implementation and impairments compensation and architecture-dependant signal processing techniques.

The accuracy of behavioural models is a key element to using digital predistortion as a method of nonlinearity compensation. Research has been conducted to extract the true static nonlinearity in wideband transmitters, which is critical in measuring the true memory effects caused by the transmitter. This finding indicates that the technique is more rigorous for de-embedding the static nonlinearity from the overall nonlinearity (static and dynamic) of the system. With memory effect modeling, algorithms based on neural networks and three-box models were conducted, showing performance improvement over traditional black box based models, such as Hammerstein and Wiener models.

The hardware implementation of an algorithm raises issues, such as precision effects and numeric instability, which are typically not seen in a simulation environment. Various digital predistorters are developed on a field-programmable gate array (FPGA) to investigate these effects. Results have shown that the orthogonal memory polynomial algorithm using fixed-point processing is more accurate than the original memory polynomial algorithm. Digital predistorters require more bandwidth than ever, as 3G+/4G (beyond 3rd generation and 4th generation) standards focus on enhancing data throughput. An adaptive predistorter was constructed using high-speed components to accommodate bandwidth up to 60 MHz for these types of signals. This predistorter will allow future generations of wireless signals to utilize the entire communications band, while meeting their spectrum emission mask. Imperfections in the hybrid RF/digital predistortion system limit the nonlinear compensation capability due to in-phase/quadrature (I/Q) imbalance in the RF vector multiplier. An algorithm was implemented on an FPGA to compensate for the I/Q imbalance using a simple look-up table (LUT), and results show significant improvement compared to no I/Q imbalance compensation.

The activities carried out within this project are supported through the iCORE research grant and the CRC grant and have been performed in close collaboration with industrial partners.

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.

One part of this project focuses on the use of a subsampling technique to concurrently down-convert multiple RF signals. The extension of the subsampling theory to nonlinear systems has been analyzed, and the simulation results show promising performance. The application of a subsampling-based receiver as an alternative solution for the feedback loop of the dual-band linearization architecture is under investigation, and the results of initial simulations of this architecture are promising. The main features of subsampling feedback loop utilization are the complexity and cost reduction of the dual-band linearization architecture. Further performance analysis and the design and optimization of proof-of-concept demonstrators are in progress.

The ongoing work on ultra-wideband 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 and, therefore, increases the battery life in mobile communications, but also allows for the design of an ultra-wideband receiver that can be used for multi-standard and multi-carrier frequencies. A prototype of the ultra-wideband receiver (2 GHz to 18 GHz) has been assembled and tested at different frequencies for WiMAX and LTE applications. New signal processing algorithms for receiver calibration and impairment compensation have been investigated. For this purpose, a one-step on-line calibration technique was proposed and tested. The use of a nonlinear calibration approach showed significant improvement in the signal quality at the baseband block of the receiver. Power detector linearization algorithms are being investigated. LUT-based predistortion has been 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. More linearization algorithms that take into account the frequency response and memory effects will be investigated in the coming year.

In this context, we also developed a new multiple-input single branch MIMO receiver using a time-multiplexed technique. An initial test on the proposed technique was conducted, and the results prove the functionality of the architecture. The development of a post-compensation technique to compensate for any gain and phase distortion, as a result of using a single branch receiver, is under investigation.

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

Multi-Band, Multi-Mode and Multi-Antenna 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 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 system for linearization purposes. The amplifier design has been fabricated and tested. A new dual-band predistortion methodology has already been established and will be implemented in an FPGA-based DSP platform. A similar RF-DPD platform suitable for dual-band application in repeaters has been developed and is under investigation.

The dual-band Doherty PA presents challenges in designing a dual-band passive component as well as a dual-band matching strategy. So far, there have been no complete solutions in dual-band matching topology for high-efficiency PA design. Thus, a thorough investigation has been done as a part of this research; and, a novel idea based on dual-band/dual-impedance quarter wave transformers has been proposed. 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 the 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. Furthermore, 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 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 PA, a RVTDNN (real-value time-delay neural network) based neural network has been developed, which has achieved comparable performances as 2D memory polynomials.

Carrier aggregation enabled transmitter architecture has been developed based on our concurrent dual-band PA and 2D-DPD platform, an energy-efficient multi-band transmitter architecture has been proposed for carrier aggregation (CA) in the LTE-Advanced (Long Term Evolution Advanced) standard. There are two advantages to using the multi-band transmitter topology compared with 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 the multi-band transmitter. This significantly reduces the power loss in the system and improves the transmitter's power efficiency. Secondly, in inter-band CA, there are scenarios in which there is no active signal in one of the frequency bands. To save 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 an SDR interface. The heart of the digital transmitter is a delta-sigma architecture, with parallel processing to improve signal processing speed. We have extended the fully digital transmitter project to include enhancements, such as support for a 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 targeting 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, has been continued this year. It was shown and validated that the CO-DPD technique can compensate for the transmitter's nonlinearities and nonlinear RF crosstalk. The cross-over multi-cell model has also been extended to 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 had 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 and multi-carrier RF transmitter is under investigation. The initial results show that using the multi-cell processing technique can significantly reduce the minimum required sampling rates of the analog-to-digital (ADC) and digital-to-analog (DAC) converters without performance degradation of the nonlinearities' compensation.

The activities carried out within this project are supported through an NSERC strategic grant and the present iCORE grant

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 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, in order to increase the bandwidth, improve the quality of the signal and enhance the power efficiency of the entire transmitter.

Two of the promising advantages of fully digital transmitter architecture are its flexibility and reconfigurability, making it suitable for 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. 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 this 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 4X1 high-speed multiplexer can be used. This digital bi-level signal is ideal to driving a very high efficient switching-mode PA. Therefore, in fully digital transmitters, it is anticipated that the advantages of reprogrammablity and reconfigurablity will be achieved for multi-band, multi-standard SDR, and application of swithing-mode PAs, which provide both efficiency and linearity for the system. Other benefits of the fully digital system would be a greater capability of integration, ease of testing and debugging, and reduced cost. In a fully digital transmitter, one drawback that should be addressed is the speed required for oversampled delta-sigma modulator. The parallel processing technique is one solution when parallel, interleaved, delta-sigma modulators are working on the signal simultaneously, in order to mitigate the required speed while maintaining the same performance.

Implementation and validation of wider band delta-sigma modulators for GHz frequency applications has been made possible with parallel processing topology and high-speed multiplexers. However, the power efficiency was relatively low. We intend to study, design and test a new delta-sigma architecture based on multi-level quantization. The architecture was briefly investigated, and preliminary results show 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 multi-level quantization delta-sigma modulators

The activities carried out within this project are supported through an NSERC strategic grant and the present iCORE grant

4. OBJECTIVES FOR NEXT YEAR

The objectives for the coming year are in line with the research directions of the Alberta Innovates Technology Futures (AITF) chair proposal, covering April 2011 to March 2016. These objectives are subdivided according to the research tracks and projects identified in the overview of the research program.

Modeling Track

Device level modeling will be continued by focusing on GaN transistors. A switch-based model for an MMIC (monolithic microwave integrated circuit) GaN transistor fabricated by NRC will be investigated. The model can be used to design different switching-mode PAs, as well as a wideband Doherty amplifier.

A load-pull measurement-based model is a new modeling candidate that is very accurate, but requires a little bit more effort. This model is based on large-signal S-parameter measurements, which can be performed in a load-pull setup. In such a model, the large-signal S-parameters and, consequently, the input and output impedances of the transistor, as well as proper impedances in order to attain certain specifications, such as output power and efficiency, can be measured and gathered together in a data-based box that can be used in a simulation process as an active device model. The major effort in generating such a measurement-based model is the extensive required measurement series. However, it will lead to greater accuracy, if the information is properly processed and compiled.

Power Amplifiers Track

During the past year, we focused on the design of high efficiency Doherty PAs using one RF input and a RF power splitter to decompose the analog signal. In the coming period, we will focus on exploiting the dual-input architecture to correct for gain imbalance between the carrier and peaking branches and to prevent drive power waste in the peaking branch at low drive levels. Working with such a multi-input architecture is expected to be challenging, in terms of input signal conditioning and time synchronization and phase coherency, as well as system level linearization of the dual-input Doherty amplifier.

Following last year's project on the determination of more accurate and better metrics for performance assessment, the nonlinear behaviour model, which is a novel approach, was proposed for automated dimension estimation in memory polynomial based PA/transmitter behavioural models. This method is based on successively identifying the static nonlinearity order and memory depth of the behaviour model. This approach is an enabling tool for efficient design optimization of PA circuits to enhance the linearizability.

A generalized memory polynomial structure that is applicable for forward modeling and linearization of direct up-conversion transmitters will be targeted and developed. The model architecture uses a unique way to model and compensate for transmitter nonlinearities and the modulator's I/Q imbalance. It is anticipated that, compared to conventional linearization techniques, this technique will provide a generalized model to predict and compensate for both frequency independent and frequency dependent transmitter nonlinearities and impairments.

DSP for Wireless Communications Track

The linearization of PAs and transmitters under wideband (60 MHz and more) drive signals will be pursued. The main limitation observed so far is mainly due to the wide bandwidth of the observation path. Accordingly, a particular interest will be given to sub-band processing techniques, in order to broaden the observation window maintaining an acceptable dynamic range and signal quality. With the bandwidth limitation and the availability of a multi-purpose smart wireless platform, there is demand for more adaptability and reconfigurability in wireless transmitters. The first and most predictable step would be the design of a multi-band wireless transmitter (or basically the PA unit of the transmitter), in which a single transmitter can concurrently support multi-bands of operation (i.e. multi-standard systems). There are ongoing projects within the group on the design and development of dual-band transmitters and, more specifically, dual-band PAs that support at least two different frequency bands.

Conventional linearization techniques, however, will not be efficient or practical 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 DPD techniques or the inefficiency of the conventional techniques as a result of neglecting the cross-modulation effects between the two frequency bands. A new dual-band linearization architecture has been developed that features distortion compensation for the concurrent dual-band transmitter. This linearization architecture consists of multiple independent signal processing cells, where each processing cell and its counterparts compensate for the distortion of one single band. For further simplification of this algorithm, there is a possible solution based on the subsampling theory. There is an ongoing effort to include the subsampling technique in the linearization architecture, in order to simplify the overall system.

Most of the initial performance testing and evaluations of the dual-band linearization architecture have been based on high-performance measurement equipment and instruments. These initial performance evaluation results are promising; and, as a next step, there is a plan to design and develop a proof-of-concept prototype of this dual-band linearization architecture. Developing a demonstration setup of this novel dual-band linearization architecture will provide a better visualization of this promising solution and will open new research ideas and challenges on this topic.

Another research topic in the DSP track is the design and development of energy-efficient transmitter architecture for carrier aggregation in 4G LTE-Advanced wireless technology. For the sake of high data rates, the LTE-Advanced standard considers the possibility of having signal transmission up to 100 MHZ bandwidth. In fact, the component carriers (CCs) of the signal in both up-link (UL) and down-link (DL) are limited to 20 MHz; however, carrier aggregation (CA) of multiple component carriers (up to a maximum of five CCs) has been introduced to broaden the overall signal bandwidth to up to 100 MHz. When it comes to realization of CA techniques, the transmitter architecture is of great importance; and, 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 based on using dual-band passive and active RF components, particularly dual-band PAs. The use of multi-band components paves the way for simple and straight-forward implementation of both intra-band and inter-band CA schemes in LTE-Advanced systems.

One of the major challenges to achieving maximum performance from MIMO transceivers is the ability to maintain acceptable levels of impairments and nonlinearities that occur due to the unavoidable implementation imperfection in the MIMO chipset design process. A new multi-cell digital predistortion processing algorithm is under development for compensation of the nonlinearities and distortions as a result of the nonlinear behaviour of the transmitter. When dealing with multi-carrier signals, distortions from the nonlinear behaviour of the RF transmitter can be classified as intra-band and inter-band distortions.

For the multi-input single-branch MIMO receiver, the proposed topology shows remarkable performance, in comparison to the conventional multi-branch MIMO receivers. However, time-multiplexing of the multiple signals introduces extra distortions into the system, which results in additional losses at the final bit-error-rate performance. The idea of using post-compensation algorithms to compensate for these distortions is under investigation.

Adaptive and Tuneable Receivers Track

In order to offer an effective solution for the design of adaptive and tuneable receivers, the main challenge is the implementation of a low-cost ultra-wideband 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 ADC 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 proved the capability of such architecture in receiving different signals. Applications 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 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 an ultra-wideband 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 received signals of a bandwidth lower than 5 MHz. Increasing the signal bandwidth results in deteriorating the signal quality (SNR degrades by more than 10 dB for a signal with 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 behaviour will be investigated to enable ultra-wideband reception capabilities in the six-port receiver. A new calibration and linearization algorithm that can be achieved in one step without having to measure each of the components of the six-port receiver separately 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.

SDR Transmitters Track

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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 power efficiency performance was relatively low. We intend to study, design and test a new delta-sigma architecture based on multi-level 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 multi-level quantization delta-sigma modulators.

The most important drawback of the proposed fully digital transmitter is the presence of quanitzation noise at the output of delta-sigma modulator. This noise can interfere with adjacent channels, reducing their quality. Also, since quantization noise will be amplified alongside the signal, even if a highly efficient switching mode PA is used, the degradation of the system efficiency is significant. Therefore, this noise should be removed or reduced before being aired. One solution may be the pulse shaping technique, where some part of the noise can be removed while the signal keeps its pulse-like shape and can, therefore, still be used to drive highly efficient switching-mode PAs.

Gigabit Millimetre-wave Transceivers Track

To satisfy the needs of continuously evolving wireless applications, wireless data rates are increasing tenfold every five years and are expected to reach one Gigabit per second (Gbps) in a few years. However, current wireless local area network (WLAN) and wireless personal area network (WPAN) standards are not capable of meeting future Gigabit rate requirements, due to the limitation on the available bandwidth and spectral efficiency for such applications. Recently, special interest has been accorded to the millimetre-wave (mm-wave) band and, especially, to the V band, where several gigahertz of unlicensed bandwidth are available around 60 GHz. While the high carrier frequency at 60 GHz is advantageous in terms of fractional bandwidth that allows for the design of ultra-wideband transceivers capable of delivering data rates well in excess of 1 Gbps with very small circuit and antenna dimensions, the high volume commercial deployment of such systems poses several challenges at technology and design levels. By using a nanoscale CMOS (complementary-metal-oxide semiconductor) technology, integration of the transmitter front-end, including the mixers, local oscillators, filters and the PA, in one chip would be possible. This will reduce the cost, size and parasitic effects, resulting in less expensive solutions with better signal quality. Two sub-tracks will be investigated initially from this perspective:

- The investigation, design and optimization of new advanced amplification architecture that provides acceptable signal quality and power efficiency performance without the need for excessive signal processing.
- The design of a low-power consumption integrated CMOS receiver using a six-port network and calibration algorithms to allow the reception of signals with data rates of several Gbps.

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 (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 of 2009-2011. Dr. Ghannouchi was inducted as a Fellow of the Royal Society of Canada (Feb. 2011). Member of the International Advisory Board of the Gigahertz Research Centre, Sweden (2007-present).
Dr. Mohamed Helaoui	iCORE 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: wireless location and communication systems	Dr. Fattouche is associated with iRadio Lab
Dr. L. Belostotski	Assistant professor Research interests: CMOS RFIC transceivers design	Dr. Belostotski is associated with iRadio Lab

VISITING PROFESSOR / RESEARCHER		
Name	Role / Topic	Awards / Special Info
Dr A. Mohammadi	Six-port and MIMO transceivers	iCORE invited professor

VISITING SPEAKERS		
Name	Topic	Special Info
Dr. C. Akyel	Invited talk: Microwave Energy Use in Industrial Medical and Scientific Applications	Professor, Ecole Polytechnique of Montreal
Dr. Francisco Falcone	Invited talk: Metamaterial Concepts and Devices: from Microwave to THz Frequency Range	Professor, University of Navarra, Spain
Dr. Francisco Falcone	Short Course : Radio Network Planning in Future Wireless Systems	Professor, University of de Navarra, Spain
Dr. Paul J. Tasker	Invited talk: RF I-V Waveform Measurement and Engineering	Cardiff University, UK
Dr. Paul J. Tasker	Short Course: RF I-V Waveform Measurement and Engineering	Cardiff University, UK

RESEARCH ASSOCIATES / ASSISTANTS		
Name	Role / Topic	Awards / Special Info
Andrew Kwan	Research associate	
Farzaneh Taringou	Research assistant / behavioural modeling of communication transceivers	
Fermin Esparza Alfero	Research assistant / wireless location and modeling	
Luc Devocht	Research assistant / all-digital transmitter implementation on a FPGA platform	

POSTDOCTORAL FELLOWS		
Name	Role / Topic	Awards / Special Info
Dr. S. Aidin Bassam	MIMO radio systems	Graduated from University of Calgary
Dr. Donglin Wang	Wireless location and channel modeling	Graduated from University of Calgary
Dr. Bogdan Georgescu	Design of CMOS transceivers	Graduated from University of Calgary
Dr. Whenhua Chen	Dual-band transceivers design	Graduated from Tsinghua University, China
Dr. Mohammad Hashmi	Wave-form engineering	Graduated from Cardiff University, UK.

PH.D. STUDENTS		
Name	Role / Topic	Awards / Special Info
Ahmet Hayrettin Yuzer	Visiting PhD student, MEU, Turkey/ Thermal memory effects modeling	Turkish Government Award, co-supervised by Dr. F. Ghannouchi and D. Simsek
Mohammadhassan Akbarpour	60 GHZ CMOS PA design	ICT – Alberta Innovates Award ,co-supervised by Drs. F. Ghannouchi and M. Helaoui
Seyed Aidin Bassam	MIMO transceivers for 4G wireless communication systems	University Award, supervised by Dr. F. Ghannouchi
Pouya Aflaki	GaN Based PA design with application to polar transmitters	University Award, supervised by Dr. F. 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. Ghannouchi
Sonia Bouajina	Behavioural modeling of RF power amplifiers with memory effects	Associate, École Nationale d'Ingenieurs de Tunis, Tunisia, co-supervised by Drs. F. Ghannouchi and M. Jaidane, graduated in January 2010
Afef Hargel	Memory-Polynomial Based models for RF transmitters linearization	Associate, Faculté des sciences, University of Tunis, Tunisia, co-supervised by Drs. A. Gharsallah and Ghannouchi
Mohammed Mojtaba Ebrahimi	Multi-band transceiver design	Co-supervised by Drs. M. Helaoui and F. Ghannouchi
Karun Rawat	Multi-standard SDR transmitters	University Award, supervised by Dr. F. Ghannouchi
Saeed Rezaei Nazifi	Generic analog linearization systems	University Award, co-supervised by Drs. F. Ghannouchi and L. Belostotski
Mehdi Vejdani Amiri	MIMO radio systems	University Award, co-supervised by Drs. M. Helaoui and F. Ghannouchi
Fahmi Elsayed	All-digital transmitter	Co-supervised by Drs. F. Ghannouchi and M. Helaoui
Dhikra Saffar	MIMO behavioural modelling	Associate, Faculté des sciences, University of Tunis, Tunisia, co-supervised by Drs. A. Gharsallah and F. Ghannouchi
Saeed Ghamari	Six-port receiver	University Award, co-supervised by Drs. M. Helaoui and F. Ghannouchi
Ramzi Darraji	Multi-mode amplifiers	ICT – Alberta Innovates Award, supervised by Dr. F. Ghannouchi
Mayada Younes	Memory effect analysis and modeling	University Award, supervised by Dr. F. Ghannouchi
Meenakshi Rawat	Neural network modeling of radio systems	University Award, supervised by Dr. F. Ghannouchi
Chokri Jbeli	Behavioural Modeling Wireless Transmitters	Associate, Faculté des sciences, University of Tunis, Tunisia, co-supervised by Drs. A. Gharsallah and F. Ghannouchi, graduated March 2011

M.SC. CANDIDATES		
Name	**Role / Topic**	**Awards / Special Info**
Abul Hassam	SDR receivers	University Award, supervised by Dr. M. Helaoui
Levent Erdogan	Use of microwave energy in tar sands applications	Associate, École Polytechnique de Montréal, co-supervised by Drs. C. Akyel and F. Ghannouchi
Shubhrajit Bhattacharjee	Wireless Channel Modeling	Co-supervised by Drs. H. Lueng and F. Ghannouchi

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. 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, one graduate student from École Polytechnique de Montréal is 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	
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 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 three Ph.D. candidates.
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.
Ningbo University, China:	Collaboration was initiated this year. Ongoing research activities are related

Prof. T. Liu	to the modeling and compensation of memory effects in RF power amplifiers.
Tsinghua Univ., 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.
Dr N. Boulejefene, and O. Hammi Hail University and KFUPM, Saudia Arabia	System level Modeling of Wireless Tranmistters
INDUSTRIAL COLLABORATIONS	
Participants	Nature of Collaboration
TRLabs, Canada: Dr. R. Davis	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: G. Brassard T. Pellerin	In the frame of a 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 the 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	The collaboration with Ericsson was initiated last year. Ericsson is currently supporting an NSERC strategic grant application related to the development of multi-mode transmitters.
Powerwave Technologies, USA: B. Vassilakis 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 Dr J. Wood Cree Corporation, USA Dr R. Pengelly,	These companies are providing LDMOS-based devices, GaN HEMTs 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, Xilinx Corporation and Altera Corporation, USA	These companies are providing iRadio Lab with DSP boards, circuits and software licences from their university program.
MathWorks, USA	MathWorks provided iRadio Lab with free software licences for special tool boxes 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
Sung-Chan Jung	Ph.D.	Doherty power amplifiers	Presently Research Professor, Sungkyunkwan University, Korea
Anwar Jarndal	Ph.D.	GaN device modeling	Presently Assistant Professor, Hodeidah University, Yemen
O. Hammi	Ph.D.	Radio signal processing	Presently Assistant Professor, KFUPM, Saudi Arabia

PH.D. CANDIDATES			
Name	Degree	Research Topic	Current Position
Chokri Jbeli	Ph.D.	Behaviour modeling of wireless transmitters	Assistant Professor, University of Tunis
W. S. EL-Deeb	Ph.D.	Waveform measurement system at RF frequencies	Postdoctoral fellow at the University of Calgary
A. S. Bassam	Ph.D.	Digital predistortion of MIMO transmitters	Postdoctoral fellow at the University of Calgary
Sonia Bouajina	Ph.D.	Behavioural modeling of RF PAs with memory effects	Assistant Professor, University of Tunis

M.SC. CANDIDATES			
Name	Degree	Research Topic	Current Position
Andrew Kwan	M.Sc.	Implementation of baseband digital predistortion techniques on a DSP/FPGA platform	Research associate, iRadio Lab, University of Calgary
Karun Rawat	M.Sc.	Dual-band RF directional couplers	Ph.D. Student, iRadio Lab
Meenakshi Rawat	M.Sc.	Radio system modeling using neural networks	Ph.D. Student, iRadio Lab
R. Darraji	M.Sc	Radio system modeling using neural networks	Ph.D. Student, iRadio Lab

8. INTELLECTUAL PROPERTY

Patents and Patent Applications:

1. F. M. Ghannouchi, S. Bensmida, M. Hashmi and M. Helaoui, "Passive source and load-pull architecture for high reflection factor synthesis ", US patent application 13097303, filed April 29, 2011.
2. S. A. Bassam, F. M. Ghannouchi and M. Helaoui, "Multi-Cell Processing Architectures for Modeling and Impairment Compensation in Multi-output systems for Multi-input Multi-output Systems", Canadian patent application 2,704,522, filed May 14, 2010.
3. S. A. Bassam, F. M. Ghannouchi and M. Helaoui, "Multi-Cell Processing Architectures for Modeling and Impairment Compensation in Multi-Input Multi-output Systems", US patent application 12/780/455, filed May 14, 2010.
4. M. Hashmi, S. Bensmida, M. Helaoui and F. M. Ghannouchi, "Novel Passive Source and Load Pull Architecture for High Reflection Factor Synthesis", US provisional patent application 61/331/944, filed May 6, 2010.

Refereed Journal Publications:

1. K. Rawat, F. M. Ghannouchi, M. Rawat and M. S. Hashmi, "Analysis of Frequency-Selective Impedance Loading of Transmission Lines for Dual-Band Couplers.," International Journal of RF and Microwave Computer-Aided Engineering Wiley, 2011 accepted.

2. 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, June 2011 accepted.

3. W. H. Chen, Y. C. Liu, L. X., Z. H. Feng and F. M. Ghannouchi, "Design of Reduced-Size Unequal Power Divider for Dual-Band Operation with Coupled Lines," Electronics Letters, Vol. 47: Issue 1, pp. 59-60, January 2011.

4. S. Tiwari, D. Wan, M. Fattouche and F. Ghannouchi, "A Novel Method for 3d Positioning in an Indoor Environment," ISRN Signal Processing, 2010 Accepted.

5. M. Lari, A. Bassam, A. Mohammadi and F. M. Ghannouchi, "Time-Multiplexed Single Front-End Mimo Receivers with Preserved Diversity Gain, Accepted in Iet-Communications Journal," IET Communications, 2010 Accepted.

6. 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, 2010 accepted.

7. M. Hashmi and F. M. Ghannouchi, "Highly Reflective Load-Pull Techniques for Microwave Power Device Characterization," Microwave Magazine, 2010 accepted.

8. 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, 2010 Accepted.

9. 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, 2010 accepted.

10. M. Younes, O. Hammi, A. Kwan and F. M. Ghannouchi, "An Accurate Complexity-Reduced “Plume” Model for Behavioral Modeling and Digital Predistortion of Rf Power Amplifiers," IEEE Transactions on Industrial Electronics, Vol. PP: Issue 99, pp. 1-9, May 2010.

11. F. Taringou, O. Hammi, B. Srinivasan, R. Malhame and F. M. Ghannouchi, "Behavior Modeling of Wideband Rf Transmitters Using Hammerstein-Wiener Models," IET Circuits, Devices & Systems, Vol. 4: Issue 4, pp. 282-290, July 2010.

12. M. Rawat, K. Rawat and F. M. Ghannouchi, "Adaptive Digital Predistortion of Wireless Power Amplifiers/Transmitters Using Dynamic Real-Valued Focused Time Delay Line Neural Networks," IEEE Transactions on Microwave Theory and Techniques, Vol. 58: Issue 1, pp. 95-104, January 2010.

13. K. Rawat, M. Rawat and F. M. Ghannouchi, "Compensating I-Q Imperfections in Hybrid Rf/Digital Predistortion with Adapted Look up Table Implemented in Fpga," IEEE Transactions on Circuits and Systems II: Express Briefs, Vol. 57: Issue 5, May 2010.

14. R. Mirzavand, A. Mohammadi and F. M. Ghannouchi, "Five-Port Microwave Receiver Architectures and Applications," IEEE Communications Magazine, Vol. 48: Issue 6, pp. 30-36, June 2010.

15. M. R. Keshavarzi, A. Mohammadi, A. Adipour and F. Ghannouchi, "Characterization of Dc Offset on Adaptive Mimo Direct Conversion Transceivers," IEICE Transactions on Communications, Japan, Vol. E94-B: Issue 1, pp. 253-261, January 2010.

16. S.-C. Jung, R. Negra and F. M. Ghannouchi, "Analysis of Miniaturized 3 Db Branch-Line Hybrid Couplers," Microwave and Optical Technology Letters, Vol. 52: Issue 7, pp. 1553-1556, July 2010.

17. C. Jebali, N. Boulejfen, A. gharsallah and F. M. Ghannouchi, "Effects of Wideband Signal for Power Amplifier Model," Microwaves & RF journal, Vol. RF& microwave amplifiers, December 2010.

18. A Jarndal, P. Aflaki, R. Negra, A. Kouki and F. Ghannouchi, "Large-Signal Modeling Methodology for Algan/Gan Hemts for Rf Switching-Mode Power Amplifiers Design," International Journal of RF and Microwave Computer-Aided Engineering, Vol. 54: Issue 7, pp. 696-700, July 2010.

19. A Jarndal, P. Aflaki, L. Degachi, A. Birafane, A. B. Kouki, R. Negra and F. Ghannouchi, "Large-Signal Model for Algan/Gan Hemts Suitable for Rf Switching-Mode Power Amplifiers Design," Solid State Electronics, Vol. 54: Issue 7, pp. 696-700, July 2010.

20. M. Helaoui and F. M. Ghannouchi, "Linearization of Power Amplifiers Using the Reverse Mm-Linc Technique," IEEE Transactions on Circuits and Systems II: Express Briefs, Vol. 57: Issue 1, pp. 6-10, January 2010.

21. M. S. Hashmi, P. J. Tasker and F. M. Ghannouchi, "Transistor Device Optimization for Rf Power Amplifier Employing Rapid Envelope Load-Pull System," International Journal of Microwave and Optical Technology, Vol. 5: Issue 3, pp. 152-161, May 2010.

22. M. S. Hashmi, P. J. Tasker, A. L. Clarke and F. M. Ghannouchi, "Measurement Infrastructure for Optimization and Characterization of Microwave Transistor Devices," International Journal of Microwave and Optical Technology (IJMOT), Vol. 5: Issue 6, pp. 345-353, November 2010.

23. M. S. Hashmi, Z. S. Rogojan, S. R. Nazifi and F. Ghannouchi, "A Broadband Dual-Inflection Point Rf Predistortion Linearizer Using Backward Reflection Topology," Progress in Electromagnetics Research C, Vol. 13, pp. 121-134, April 2010.

24. M. S. Hashmi, Z. S. Rogojan and F. M. Ghannouchi, "A Flexible Dual-Inflection Point Rf Predistortion Linearizer for Microwave Power Amplifiers," Progress in Electromagnetics Research C, Vol. 13, pp. 1-18, April 2010.

25. M. S. Hashmi and F. M. Ghannouchi, "Experimental Investigation of the Uncontrolled Higher Harmonic Impedances Effect on the Performance of High-Power Microwave Devices," Microwave and Optical Technology Letters, Vol. 52: Issue 11, pp. 2480-2482, November 2010.

26. M. S. Hashmi, A. L. Clarke, J. Lees, M. Helaoui, P. J. Taskar and F. M. Ghannouchi, "Agile Harmonic Envelope Load-Pull System Enabling Reliable and Rapid Device Characterization," IOP Journal of Measurement Science and Technology, Vol. 21: Issue 055109, pp. 1-9, April 2010.

27. O. Hammi, M. Younes, A. Kwan, M. Smith and F. M. Ghannouchi, "Performance-Driven Dimension Estimation of Memory Polynomial Behavioural Models for Wireless Transmitters and Power Amplifiers.," Progress in Electromagnetics Research (PIER-C), Vol. 12, pp. 173-189, 2010.

28. O. Hammi, M. Younes and F. M. Ghannouchi, "Metrics and Methods for Benchmarking of Rf Transmitter Behavioral Models with Application to the Development of a Hybrid Memory Polynomial Model," IEEE Transactions on Broadcasting , Vol. 56: Issue 3, pp. 350-357, September 2010.

29. F. M. Ghannouchi, "Power Amplifier and Software Defined Radio Systems," IEEE Circuits and Systems Magazine, Vol. 10: Issue 4, pp. 56-63, 11 2010.

30. F. Ghannouchi, S. Hatami, P. Aflaki, M. Helaoui and R. Negra, "Accurate Power Efficiency Estimation of Ghz Wireless Delta-Sigma Transmitters for Different Classes of Switching Mode Power Amplifiers," IEEE Transactions on Microwave Theory and Techniques, Vol. 58: Issue 11, pp. 2812-2819, November 2010 2010.

31. F. Ghannouchi, M. S. Hashmi, S. B. Smida and N. Boulejfen, "Loop Enhanced Passive Source- and Load-Pull Technique for High Reflection Factor Synthesis," IEEE Transactions on Microwave Theory and Techniques, Vol. 58: Issue 11, pp. 2952-2959, November 2010.

32. W. S. El-Deeb, M. S. Hashmi, F. M. Ghannouchi, N. Boulejfene and S. Bensmida, "Thru-Less Calibration Algorithm and Measurement System for on-Wafer Large-Signal Characterization of Microwave Devices," IET Microwaves, Antennas and Propagation, Vol. 4: Issue 11, pp. 1773-1781, November 2010.

33. W. S. El-Deeb, N. Boulejfen and F. M. Ghannouchi, "A Multi-Port Measurement System for Complex Distortion Measurements of Nonlinear Microwave Systems,," IEEE Transactions on Instrumentation and Measurement, Vol. 59: Issue 5, pp. 1406-1413, May 2010.

34. W. S. El-Deeb, S. Bensmida, N. Boulejfen and F. M. Ghannouchi, "An Impedance and Power Flow Measurement System Suitable for on-Wafer Microwave Device Large Signal Characterization " International

Journal of RF and Microwave Computer-Aided Engineering Journal, Vol. 20: Issue 3, pp. 306-312, February 2010.

35. M. M. Ebrahimi, F. M. Ghannouchi and M. Helaoui, "Analytical Approach to Optimize the Efficiency of Switching Mode Pas Loaded with Semi-Distributed Matching Networks," IET Microwaves, Antennas and Propagation, Vol. 5: Issue 1, p. 57, January 2011 2010.

36. N. Boulejfen, A. Harguem, O. Hammi, F. M. Ghannouchi and A. Gharsallah, "Analytical Prediction of Spectral Regrowth and Correlated and Uncorrelated Distortion in Multicarrier Wirless Transmitters Exhibiting Memory Effects," IET Microwaves, Antennas & Propagation, Vol. 4: Issue 6, pp. 685-696, June 2010.

37. S. S.-. Bouajina, O. Hammi, M. Jaidane-Saidane and F. M. Ghannouchi, "Experimental Approach for Robust Identification of Rf Power Amplifier Behavioral Models Using Polynomial Structures," IET Microwaves, Antennas & Propagation, Vol. 4: Issue 11, pp. 1818-1828, November 2010.

38. Birafane, M. El-Asmar, A. B. Kouki, M. Helaoui and F. M. Ghannouchi, "Comprehensive Analysis of Linc Power Amplifiers from Efficiency and Linearity Perspectives," IEEE Microwave Magazine, Vol. 11: Issue 5, pp. 59-71, August 2010.

Refereed Conference Proceedings:

1. 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 , Spokane, Washington, July 3-8, 2011 accepted.

2. 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 , Niagara Falls, Ontario, May 8-11 2011 accepted.

3. Saeed Rezaei Nazifi, Mohammad S. Hashmi, B. Dehlaghi and F. Ghannouchi, "Systematic Methodology to Design Analog Predistortion Linearizer for Dual Inflection Power Amplifiers," in International Microwave Symposium (IMS2011), Blatimore, Maryland, June 5-11 2011 accepted.

4. K. Rawat and F. Ghannouchi, "C-Band Microstrip Based Band-Pass Filter with Design Oriented Transmission Zeros Allocation," in 24th Canadian Conference on Electrical and Computer Engineering, Niagra Falls, Ontario, May 8-11, 2011 accepted.

5. 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 IEEE AP-S International Symposium on Antennas and Propagation and 2011 URSI National Radio Science Meeting , Spokane, Washington, July 3-8 2011 accepted.

6. W. S. El-Deeb, M. S. Hashmi, N. Boulejfen and F. Ghannouchi, "Time-Domain Waveform Measurement System for the Characterization of Mimo Rf Power Amplifiers,," in The 12th annual IEEE Wireless and Microwave Technology Conference, WAMICON 2011,, Florida, USA, 18-19 April, 2011 accepted.

7. 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 Communications and Networking Symposium of the IEEE Canadian Conference on Electrical and Computer Engineering 2011, Niagara Falls, Ontario, May 11-18, 2011.

8. W. S. El-Deeb, M. S. Hashmi, N. Boulejfen and F. M. Ghannouchi, "Relative Waveform Measurement Technique for the Characterization of Multiport Microwave Devices," in 2010 IEEE International Symposium on Antennas and Propagation and CNC/USNC/URSI Radio Science Meeting, Toronto, ON, 11-17 July 2010 accepted.

9. M. S. Hashmi and F. M. Ghannouchi, "Recent Advances in the Load Synthesis Approaches for Characterization of Microwave Devices Employed in Power Amplifier Design," in 2010 IEEE International Symposium on Antennas and Propagation and CNC/USNC/URSI Radio Science Meeting, Toronto, ON, 11-17 July 2010 accepted.

10. M. M. Ebrahimi, S. A. Bassam, M. Helaoui and F. M. Ghannouchi, "Packet Detection, Frequency Synchronization, and Channel Estimation/Equalization of Reconfigurable Ofdm-Based Receivers for Sdr Applications," in Wireless Innovation Conference, Washington DC, USA, pp. 87-93, 30 November - 3 December 2010.

11. F. E. Alfaro, M. Rawat, R. Darraji, K. Rawat, V. Torres, F. Falcone and F. M. Ghannouchi, "Rf Environment Behavior Modeling Based on 3-D Ray-Tracing and Neural Networks to Mitigate Multipath in Indoor Position Estimation," in Wireless Innovation Conference, Washington DC, USA, pp. 82-86, 30 November - 3 December 2010.

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18. W. S. El-Deeb, M. S. Hashmi, N. Boulejfen and F. M. Ghannouchi, "Dynamic Distortion Characterization of Multiport Rf Pas Using Mta-Based Multiport Measurement Setup," in Integrated Nonlinear Microwave and Millimeter-Wave Circuits (INMMIC'2010), Goteborg, Sweeden, pp. 152-155, 26-27 April 2010.

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Books and Chapters:

Six-Port Techniques with Microwave and Wireless Applications, F.M. Ghannouchi and A. Mohammadi, Editor, Artech House: (April 2010)

Special/Invited Presentations:

1.

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 won the finals in the SDR Challenge 2010-, Washington, DC, April, 2010.

- iRadio lab attended the 2010 International Microwave Symposium and Exhibition in Anaheim, CA (http://www.ims2010.org/), where they showcased hardware-software solutions developed to reduce the energy consumption of wireless radio terminals.

11. FINANCIAL REPORTS

ICORE Revenues/Expenses

The annual financial statement will be sent directly to iCORE 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
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