



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) 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 Chair was granted by Alberta Innovates Technology Futures (AITF) for an additional five-year period starting May 1st, 2011 and extended upon the request of the Chairholder to April 30, 2018.

The present research program is a continuation and reinforcement of the research and development (R&D) activities conducted at iRadio Lab during its last ten-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 the building on the success of past achievements to seamlessly align the R&D activities toward gigabit (Gbit) software-defined radio (SDR), green communications and multiple-input multiple-output (MIMO) and multi-antenna (MA) systems. The planned research program for this second mandate is concerned with the development of relevant and enabling technologies for 5G (5th generation) wireless communications and Internet of Things (IoT) related 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 and MA 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-five graduate students and researchers, who have been recruited from around the world. The main space dedicated to iRadio Lab in the University of Calgary's ICT building (ICT 305 and ICT 318) is being used as offices for graduate students and research staff, as well as the research program's main instrumentation, simulation and design area. An auxiliary space in A Block of the Engineering Building (ENA 5) is also being utilized by graduate students and researchers for printed circuit board fabrication, prototyping and storage of newly procured equipment for the Canada Foundation for Innovation (CFI) funded mm-wave facility until new space can be allocated by the department for this new facility. This new mm-wave facility is composed of the latest, state-of-the-art signal generation and analysis equipment (up to 2 GHz bandwidth modulated signals) and offers the capabilities of ultra-wideband on-wafer measurement capabilities at mm-wave frequencies (up to 67 GHz).

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 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 in this past year have led to 17 refereed journal papers (published and accepted), 31 refereed conference papers (published and accepted), 8 patent

applications, 5 US patents allowed and the publication of two book chapters. Three keynote and invited talks were given by iRadio Lab researchers at international conferences and leading research institutions and universities. A Ph.D. student, Tushar Sharma, was awarded an AITF-ICT scholarship; and, a second Ph.D. student, Andrew Kwan, was the recipient of an NSERC (Natural Sciences and Engineering Research Council of Canada) Ph.D. Award. Xiang Li was the recipient of an AITF Doctoral Award for Chinese Students.

During its tenth year, iRadio Lab was successful in securing substantial funding from NSERC: \$181 K. These monies supplemented the \$944 K, \$200 K and \$150 K yearly averages provided by AITF, the Canada Research Chairs (CRC) program and the University of Calgary, respectively. In addition, in-kind contributions and equipment donation in the amounts of about \$330 K from industry partners, \$100 K from MCM, and \$200 K 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 last year, totalling an annual average of \$161 K.

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, three associated faculty members, one technical support staff, one administrative support staff, two lab managers, four postdoctoral fellows and twenty-three graduate students.

Research Partners

iRadio Lab has been mainly funded by the joint sponsorship of AITF, CRC, NSERC and 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 based transceivers. In addition, close collaborations have been made with major leading national and international companies and agencies

Major Research Directions

The scope of this AITF/CRC research program is related to the development of intelligent and green RF radio systems for emerging wireless and satellite communications. The main goal is the development of software-defined, high-performance, environmentally friendly transceivers. This multidisciplinary research calls for broad knowledge in the fields of digital signal processing (DSP), mixed signal technology and 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 research directions that were identified in the Chair's renewal proposal.

All the current and planned activities of iRadio Lab are in line with the Chair's 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, MIMO/MA communication systems. The optimization of power-added efficiency, due mainly to the reduction in direct current (DC) power consumption of RF radios, is one of the objectives of the research program, as initially stated in the Chair's renewal 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.

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 transceivers, as well as in predistortion, impairment compensation and pre- or post-equalization applications.

Green microwave technology: The power amplifier (PA) is the most critical and expensive subsystem in all RF wireless systems, as its performance significantly affects 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, 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 the desired functionality and optimal system-level performance. This includes impairment pre-compensation and architecture-dependent signal processing and conditioning.

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

Adaptive 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, multi-standard communications systems.

Millimetre wave (mm-wave) electronics: With the increasing demand for high data rates, Gbps (gigabit/second) communication has become a necessity in recent years. Such speeds cannot be achieved by transceivers with carrier frequencies located in the lower frequency bands, such as UHF, L or S bands. By moving to higher carrier frequencies (mm-wave bands), one can achieve high data rate transmissions, but at considerably higher design costs and degraded linearity performance and energy efficiency. Therefore, there is a necessity to propose new transceiver architectures suitable for these high-frequency ranges that guarantee better linearity and energy consumption, while maintaining low cost and complexity.

3. RESEARCH TRACKS

The research program is being conducted in the aforementioned six major research directions. The achievements related to each of these tracks are reported and evaluated in relation to the main goals stated in the Chair's renewal research proposal.

Microwave and Radio Frequency (RF) Device Characterization and Modeling

The research activities in this track have been supported by an NSERC grant, the CRC Chair grant and the AITF Chair grant.

Broadband switching-mode PAs: The RF microwave power amplifier (PA) is a key element in transmitter systems. PA requirements mainly consist of the absolute achievable output power levels in conjunction with highest efficiency and linearity performances. A common disadvantage of linear PAs compared to their nonlinear counterparts is their substantially lower power efficiency. Since the PA is the component that consumes most of the power in transmitters, such as base stations, this low power efficiency and consequently higher power consumption translate directly to high operating expenses and a significant unpleasant environmental impact through heat dissipation, both of which are no longer tolerated. Energy efficiency solutions necessitate R&D of radio networks to implement green RF-PAs.

Among new transmitter technologies to reduce the power dissipation, the switching-mode technique achieves efficiencies up to 70-80%. However this method suffers from limited frequency bandwidth and works at relatively low RF frequencies. Due to the switching behaviour, nonlinearity is also a serious problem in this method. Improving the performance of switching-mode power amplifiers (SMPAs) is one of the main topics in transmitter architecture research.

To improve the frequency bandwidth of SMPAs to reach one octave, a mode transferring method was proposed. This technique helps in extending the bandwidth by allowing the PA to operate in a given class for half the band and another different class for the remaining band. The concept of in-band mode transfer was used between class-F and inverse class-F modes of operation. The PA, which was designed using a 10-watt gallium nitride (GaN) device, exhibited a drain efficiency of greater than 70%, a power gain higher than 13 dB, and an output power of more than 10 watts over the frequency band ranging from 460 to 920 MHz, which corresponds to an octave bandwidth or 67% of the fractional bandwidth.

A methodology for the realization of input and output matching networks for wideband SMPA design was also developed. The proposed design approach was validated using the Cree CGH40010 (packaged 10 W GaN transistor). Under a continuous wave (CW) test condition, the fabricated PA exhibited drain efficiency greater than 75% over 58% of the fractional bandwidth (500-900 MHz). The designed broadband PA is suitable for delta-sigma modulation based transmitters, linear amplification with nonlinear components (LINC) systems, and Doherty PAs. The PA has demonstrated an average drain efficiency higher than 35% over the frequency band when driven with a 20 MHz bandwidth LTE (Long Term Evolution) communication signal.

The design of broadband class-E SMPAs was also considered. In addition to the high efficiency that class-E PAs offer, the low sensitivity for duty cycles is an advantage of this class of operation compared to other SMPAs. This benefit makes class E the preferred PA topology for delta-sigma based transmitters. However, class-E PAs still suffer from limited bandwidth as other SMPAs. A technique for designing input and output matching networks for a broadband class-E SMPA was proposed and validated using two different transistors from Cree (packaged 6 W and 25 W transistors). The fabricated PAs showed drain efficiencies higher than 60% for the 25 W device and 65% for the 6 W transistor over a large bandwidth that included different bands from the LTE standard (from 1.8 GHz to 2.7 GHz).

Continuous-mode PAs: Applications of the continuous-mode concept were investigated in the design of broadband PAs biased below the pinch-off voltage in low- and high-power class-C (LPC and HPC, respectively) modes. With the generic drain current waveform depending on the amplifier conduction angle and use of the well-established continuous class-B (class-J) voltage waveforms, a set of closed-form equations for the fundamental and second harmonic impedances were derived. These provide a wide impedance design space to realize broadband class-C PAs in two low- and high-power modes with constant output power, gain and efficiency over a significant bandwidth.

These concepts were validated through practical implementation of an integrated GaN MMIC (monolithic microwave integrated circuit) technology provided by Canadian Microsystem Corporation (CMC). An integrated class-J PA was designed and its RF characteristics were simulated in Agilent ADS simulator software. As part of a journal paper published in *IEEE Transactions on Microwave Theory and Techniques*, we presented the PA RF characteristics versus the frequency sweep from 1.5 GHz to 3 GHz. With the continuous class-C concept, the gate bias voltage was changed to allow the PA work in the class-C condition. By adjusting the input power, the new high-power class-C amplifier showed similar performance under the class-C condition. The use of one structure of an amplifier in two different modes of operation was an outcome of this research. With the design of a new output-matching network, the amplifier performed in low-power class-C mode. In this mode of operation, the input power remained as it was in the class-J mode of operation. It was shown and validated that the integrated PAs were able to maintain a constant output power and power-added efficiency (PAE) in all class-J, LPC and HPC modes at different frequencies over a specific bandwidth.

Green RF Power Amplification Systems

The activities carried out within this research direction have been supported through an NSERC Collaborative Research Development grant.

Digital Doherty PAs: In continuation of work done in the previous year, we developed a solution to enable Doherty amplifier based wireless transmitters to support ultra-broadband and concurrent multi-standard signals. In this context, we proposed a frequency-agile transmitter architecture that incorporates a digital baseband equalizer in its digital signal processing (DSP) unit. The equalizer was implemented using finite impulse response digital filters to improve the efficiency of the radio transmitter in the context of ultra-wideband and concurrent multiband signals. When driven with a 140-MHz bandwidth carrier aggregated LTE signal, the average transmission efficiency with digital baseband equalization was enhanced from 33.5 to 44.7%. Moreover, its linearity performance, in terms of adjacent channel leakage ratio (ACLR), was improved from -21 to -26 dBc. In the concurrent dual-band test, the baseband equalizer permitted a reduction in the DC power consumption by 15%. As such, the proposed architecture was demonstrated to boost the overall power efficiency without compromising the linearizability of the wireless transmitter.

The impact of the finite OFF-state impedance of the peaking branch on the efficiency response of the Doherty PA was also investigated. We studied this problem for laterally diffused metal oxide semiconductor (LDMOS) field effect transistors (FETs), as well as for GaN high electron mobility transistors (HEMTs). It was demonstrated that GaN HEMTs possess superior material properties that make them very suitable for the design of high-efficiency Doherty PAs. For this reason, we generally use GaN-based devices in designing highly efficient Doherty PAs.

Integrated load-modulated PAs: A proposed compact Doherty amplifier with three-port input and output networks was validated by measuring the performances of two prototypes. The proposed amplifier can be designed for arbitrary source and load impedances, an arbitrary power division ratio at the input, and an arbitrary output power ratio from the two branches using very compact input and output networks. There is a theoretical limit to the back-off efficiency at the power back-off of Doherty amplifiers, thereby limiting its performance at power back-off to a suboptimal level. However, the use of the proposed amplifier structure guarantees optimal performance in terms of back-off efficiency. A paper describing the proposed design procedure and the results obtained from the prototypes has been submitted to *IEEE Transactions on Microwave Theory and Techniques*.

Advanced Adaptive DSP Algorithms for Wireless Transceivers

These projects have been supported by the AITF research grant, NSERC and the CRC Chair Grant.

MIMO transmitters: To accommodate more users and increasing demand for faster data rates, multiple-input multiple-output (MIMO) architectures are being increasingly adopted by the wireless communication industry. With the recent developments in millimetre wave (mm-wave) technologies, large-scale MIMO (known as massive MIMO) systems are being considered for use in the upcoming 5G standards, with antenna arrays sized up to 256×256 . Due to large-scale integration and the limited isolation between MIMO transmitter paths, the signals in different paths interact with one another. This phenomenon is known as crosstalk, which can occur either before the PA (nonlinear crosstalk) or after the PA (linear crosstalk). Typically, the crosstalk and PA nonlinearity are jointly compensated for by utilizing 2x2 digital predistortion (DPD) in a 2x2 MIMO transmitter, which is associated with high computational and implementation costs. To streamline this process, a novel technique that estimates two 1x1 DPD has been proposed and successfully deployed to linearize a 2x2 MIMO transmitter at half the computational complexity of the 2x2 DPD.

A technique based on the use of lattice filters for a reduction in the numerical instability issues associated with application of DPD for MIMO systems has also been proposed. The adoption of this technique enables the implementation of stable and reliable low-cost MIMO DPD that uses a maximum of 16 bits.

Transceiver hardware impairments: The digital domain linearization/correction of different RF imperfections are important for improving the performance of transceivers. The PA is the most nonlinear device in any conventional transmitter and the main source of nonlinear distortions; however, the low-noise amplifier (LNA) at the receiver can also be a cause of nonlinear distortion. Other major RF impairments, such as in-phase / quadrature (I/Q) imbalance, phase noise (PN) and carrier frequency offset (CFO), result in various problems and make the detection of the signal difficult at the receiver. The antenna and non-constant group delay variations in band-pass filters also cause distortions. It is important, therefore, to alleviate these imperfections with reduced complexity algorithms. The joint effects of both the transmitter and receiver's imperfections can be eliminated at the receiver. For this purpose, the effects of the wireless channel are also considered when formulating different methods to correct the aforementioned imperfections. Post-compensation methods lead to reduced transmitter complexity from both hardware and software perspectives. Simulations of the combined distortion and impairments effects of the transmitter, channel and receiver have been carried out and appropriate pre-compensation at the transmitter side and post-compensation at the receiver side algorithms to mitigate these unwanted effects are under development.

The joint effects of both the transmitter and receiver's imperfections can be eliminated at the receiver. For this purpose, the effects of the wireless channel are also considered when formulating different methods to correct the aforementioned imperfections. Post-compensation methods lead to reduced transmitter complexity from both hardware and software perspectives.

SDR Transmitters

The activities carried out within this research direction have been supported through an NSERC Collaborative Research grant, AITF funds, and cash and in-kind contributions from Ericsson Canada.

Software-defined radios provide the flexibility of altering RF characteristics through software reprogramming. One focus is the conversion of all the restrictive analog RF components into desirable digital forms. Delta-sigma modulators (DSMs) are used to convert the normal low-speed baseband signal into a high-speed, binary-like form, where changing the speed sets the desired transmitted frequency band. Utilizing these binary or multi-level signals, high-efficiency SMPAs (switching-mode power amplifiers) can be deployed in transmitters. An additional topology that can be used is RF digital-to-analog converters (RFDACs), where the normal frequency mixing is replaced with components that introduce less distortion and noise at the output of the transmitter while allowing for reconfigurability.

All-digital delta-sigma based transmitter: This approach utilizes a dual branch (delta, sigma) in order to enhance the throughput of a multi-standard DSM and increase the parallelization level of the building blocks. Techniques for noise quantization level reduction can significantly enhance the coding efficiency of the DSM. For up-conversion to RF frequencies, a multiplexer is used at the output of the DSM. This up-conversion technique offers more flexibility and a wide range of carrier frequencies (10 MHz - 2.5 GHz). The transmitter was tested using a continuous wave signal and an LTE signal with a bandwidth of 2 MHz. A full transmitter that integrated both an SMPA stage and a band-pass filtering stage was tested and validated. The obtained results show improvements in terms of adjacent channel power ratio (ACPR) and coding efficiency compared to those of the single-branch topology. This work continues through investigation of increasing the processing speed to enable the transmitter to send signals with larger bandwidths.

Integration of a complex delta-sigma transmitter on an SDR platform: A complex, three-level, delta-sigma modulator (DSM) topology, based on an adaptive noise suppression technique, was proposed. This architecture offers considerable improvements in performance in terms of bandwidth, power efficiency and coding efficiency compared to Cartesian modulators. This transmitter was implemented on an SDR platform from BEEcube Inc. Digital predistortion (DPD) was used to compensate for the hardware impairments due to transceivers of the RF front-end. The outputs of the dual-channel transmitter were fed to a class-E PA and then combined. The performance of the DSM transmitter was evaluated using an LTE signal with a bandwidth of 1.4 MHz. A coding efficiency of 72% and an in-band efficiency of 31% were obtained for a signal with an average output power of 32 dBm.

Pulsed load modulation transmitters: In the continuation of the research on pulsed load modulation (PLM) transmitters, a complete transmitter architecture based on a 10 W GaN HEMT was designed and implemented for efficient base station applications. The transmitter prototype was developed by implementing a high power envelope gate modulated PA. In the proposed scheme, an appropriate strategy has been implemented to condition gate pulses in order to switch 10 W GaN devices at high speed.

A level shifter interface circuit was designed and fabricated to change the voltage levels of the pulses generated from the field programmable gate array (FPGA) to levels that can switch PAs between ON and OFF states. The envelope of the original signal was digitized by a 1-bit second-order envelope DSM (EDSM) using a high-speed FPGA from Altera Corp. The constant envelope modulated signal was then transmitted to the gate biases of the main, auxiliary and digital driver amplifiers through level-shifter interface circuits. The phase of the signal was up-converted to the carrier frequency through a wideband I/Q modulator. In order to investigate the load modulation behaviour of the PA, the transmitter prototype was first tested with pulse trains and various duty cycle values.

The designed PA demonstrated enhanced efficiency compared with the balanced class-B amplifier (e.g. 12% enhancement in the drain efficiency at the 6 dB output back-off region). Practical standards' signals, such as LTE, WiMAX (Worldwide Interoperability for Microwave Access) and WLAN (wireless local area network) signals, with various peak-to-average power ratios (PAPRs) have been also used to verify the performance of the complete transmitter prototype and the linearity of the PA. Experimental results show that, for signals with PAPRs less than 6 dB, the average drain efficiency of designed PA was greater than 54%. The performance of the transmitter has been successfully tested using an LTE downlink signal with PAPRs of 5 and 6 dB, and experimental results show that the output signal spectrum satisfied the LTE emission mask.

All-digital three-way amplitude modulation based transmitter: In this project, a new transmitter architecture that uses only envelope modulators was proposed. This topology translates the baseband phase signal to the RF domain without the use of mixers and quadrature up-converters. Hence, spurious signals and distortions typically associated with mixer circuits are avoided over a wide frequency band, and no filtering is needed to meet the spectrum emission mask. The absence of an RF band-pass filter eliminates the operating frequency constraint and makes the transmitter design reconfigurable and more integrable. This architecture does not use a phase modulator circuit and avoids bandwidth constraints. The performance of the transmitter was successfully tested using LTE signals, and the signal quality was assessed in terms of error vector magnitude.

Adaptive and Tuneable Receivers

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

Wideband and multiband radio receivers are highly desirable for the flexibility provided to the receiver chain. Subsampling and six-port receivers are two technologies that offer high receiver tuneability and reconfigurability. In subsampling receivers, traditional sampling frequency theory is ignored; and, all signals are captured into an analog-to-digital converter (ADC). A differentiator at the receiver front-end allows the user to select the signals to capture. In six-port receiver designs, the demodulation stage is replaced with broadband passive components. These six-port receivers were tested under fading environments and dual-band conditions.

Subsampling receivers: Current RF receivers require a mixing stage to down-convert the RF signal into a lower frequency suitable for digitization by the ADC. A cost-effective alternative is the removal of the entire down-conversion unit and direct sampling of the signal in RF. However, this violates the conditions of traditional sampling requirements. This solution, also called subsampling, requires careful selection of the sampling frequency in order to be able to recover the signal.

The presence of intermodulation (IM) products in a nonlinear system poses challenges in a subsampling receiver. These unwanted signals can be classified as interference, where the original signals to be captured are severely distorted if they fall in the same frequency. However, the IM products may be able to distort each other, since they are not of interest. A modified version of a multiband subsampling algorithm was proposed to alleviate constraints of the subsampling frequency selection, while increasing the range of frequencies available by allowing the unwanted signals to overlap with each other.

Ultra-wideband six-port based direct conversion receivers: The DSP algorithms that were previously developed for single- and dual-band ultra-wideband (UWB, 2-18 GHz) receiver prototypes are very complex, as are their respective calibration models. A calibration model with reduced complexity was proposed to lessen the calibration effort, while keeping the overall receiver performance comparable to the previously developed algorithms. Research is in progress for extending the application and suitability of this reduced complexity calibration approach to concurrent dual-band six-port receiver applications.

A comprehensive study identified the advantages and disadvantages of an existing diode-based six-port receiver. Receiver selectivity and the accompanying non-idealities with the diode-based power detectors were found to be key areas where desired performance was lacking. Research is ongoing on a new six-port based receiver architecture that removes the uses of diode power detectors, while at the same time increases the selectivity and other performance metrics of the six-port receiver.

The use of the six-port receiver in real communication systems for MIMO and cognitive radio applications was also investigated.

Concurrent dual-band six-port receivers: Concurrent dual-band receivers allow a mobile terminal's users to simultaneously access two wireless services and enable infrastructure sharing of base stations between different operators. They are also applied in spectrum aggregation systems to increase communication throughput, utilizing transmission and reception in two frequency bands.

Conventional architectures use the front-end stack-up technique, whereby two receiver paths are integrated together with each path dedicated to receiving signals from one band. This, however, increases the size, cost and power requirements of the receiver. The six-port receiver option has been explored as an alternative, and a novel concurrent dual-band six-port receiver was successfully designed and implemented. This dual-band receiver uses the same architecture as in the single-band case without duplicating the receiver path.

In addition to this hardware design, DSP algorithms were developed for nonlinear calibration of the concurrent dual-band receiver. The developed receiver and calibration technique improved performance significantly, enabling its use for receiving real communication signals. In order to verify that the developed receiver can operate in multi-standard and multiband scenarios, WCDMA (wideband code division multiple access) and LTE signals were transmitted separately in two selected bands and received concurrently using the proposed receiver, demonstrating the usefulness of the receiver in real communication systems. The performance of the six-port receiver was analyzed in terms of linearity, complexity and power consumption. The obtained results were compared with a low intermediate frequency (IF) receiver to show the superiority of the proposed topology.

The performance of the calibrated six-port receiver was assessed in the presence of a frequency selective wireless communication channel. The proposed DSP algorithms for modeling and calibration of the six-port receiver take into account these channel effects. These new algorithms were able to calibrate the six-port receiver as well as equalize the channel effects. Furthermore, optimization of the algorithms was carried out, decreasing their complexity by reducing the number of coefficients for the models used in calibration and post-compensation by a factor of three times, without affecting the linearity performance of the overall system.

Multiband and Multimode SDR-Based Transmitters

Software defined radios (SDRs) are becoming more promising due to their flexible architecture, and as wireless standards evolve, multiband transmitters will be a requirement for increasing data rates. For example, the system configuration in the LTE Advanced (LTE-A) standard can differ between single-band and multiband transmission techniques, such as inter-band and intra-band carrier aggregation (CA). A strategy must be employed by system architects to handle the design of these transmitters under all configurations of operation.

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

Linearization of broadband transmitters: To keep up with the increasing demand for higher data rates, CA techniques have been widely adopted by the wireless communications industry. The use of CA, however, brings with it new challenges for DPD (digital predistortion), such as stronger transmitter nonlinearities and more significant memory effects. To address these challenges, a novel Volterra-based CA digital predistorter was proposed. This DPD was then used to successfully linearize a highly nonlinear Doherty amplifier prototype, driven by a 100 MHz carrier-aggregated LTE-A signal. To further improve the model, a novel DPD complexity-reduction technique based on compressed sampling (CS) theory was developed and combined with the model. The digital predistorter and complexity-reduction technique were then successfully applied to a two-input envelope-tracking PA, reducing model parameters while being able to meet spectral requirements. Another approach to the reduction of DPD model complexity, which utilizes radial pruning of Volterra series models, was proposed for linearizing multi-band transmitters.

The bandwidth of the signal at the output of the PA is crucial when attempting to model the PA and generate the model parameters of the DPD. One solution is the capture of less than the required bandwidth and approximation of the model extracted by band limited signals utilizing adaptive basis functions. It has been shown that the reduction in spectral regrowth is acceptable, while reducing the ADC (analog-to-digital convertor) rate and eliminating a cavity filter for the feedback loop.

Another solution to limit bandwidth is the utilization of a two-box model for DPD, where the static nonlinearity is initially de-embedded using a low-frequency signal. Static nonlinearity is the source of the spectral regrowth and directly relates to the bandwidth requirement for capturing the PA output signal. The adaptation for DPD is performed by only updating the dynamics of the system. A 60 MHz carrier aggregated LTE-A signal was used, and the results proved that the ADC sampling rate required for the feedback loop could be reduced by approximately 60 percent.

Envelope tracking for multiband transmitters: The efficiency characteristics of a PA are improved with lower supply voltage; hence, a dynamic adjustment of the supply voltage can help increase power efficiency. In typical applications, the voltage is adjusted by calculating the input signals' envelope, which is also called envelope tracking (ET). When the signal at the input of the PA increases in bandwidth, the envelope of the signal also increases. Thus, low-frequency equivalent envelope functions must be used such that the modulator is a representation of the true wide bandwidth envelope. A comparison was conducted for a dual-band signal to determine the effectiveness when capturing a wideband output compared with the individual bands in an ET configuration. The results showed that the use of ET architectures increases the average drain efficiency by 8% compared with the fixed supply case, at a negligible cost in terms of the adjacent channel power ratio (ACPR) and error vector magnitude (EVM) performance.

Another problem that exists in an intra-band CA configuration is the transmission of several signals within the allotted frequency band. In such a scenario, the maximum envelope bandwidth is generated when signals are sent at the transmission limits of the band. An extended phase-aligned digital predistorter was developed for concurrent tri-band PAs. The placement of the carriers was derived such that the signals' intermodulation overlaps and causes difficulties for the predistorter. It was shown that under ET configuration, a boost in efficiency was experienced, while maintaining the ACPR and EVM specifications.

Integrated Circuit Design – Microwave and Millimetre Wave

The growing demand for high-performance and low-cost integrated systems requires a great deal of research on integrated circuits, especially for microwave subsystems. One of the important parts of a wireless system 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 PAs can be achieved.

The activities carried out within these projects of integrated designs for microwave and mm-wave applications 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. These projects have also been supported through an NSERC discovery grant and AITF funds.

GaN PAs: A recently proposed continuous-mode linear class-J mode of operation, with proper fundamental and second harmonic impedances, is a promising solution for the linearity, efficiency and bandwidth requirements in a single-ended PA design. Class-J Originated from the linear class-B operation mode and has been theoretically shown to achieve output power, gain and efficiencies as high as those of class-“deep” AB and class-B PAs. In addition, class-J PAs are expected to achieve broad bandwidth operations with the proper impedances to the transistor current source over a specific design space. Broadband behaviour of such amplifiers is achieved by mapping each point on the design space to a single frequency point. This contributes to the design of broadband output matching networks with much less complexity than traditional broadband matching circuits.

The design of GaN (gallium nitride) MMIC (monolithic microwave integrated circuit) class-J PAs and the analytical study and quantitative analysis of the power-efficiency design paradigm have been carried out during last few years. Several prototype were fabricated with CMC support. A class-J PA was fabricated in a GaN technology to verify the accuracy of the theoretical design procedure and the simulation results. The fabricated broadband 0.5 W GaN MMIC class-J amplifier with 15 V DC supply voltage experimentally demonstrated a drain efficiency of at least 50% in more than 800 MHz of bandwidth from 2.25 GHz to 3.075 GHz. This was the world's first integrated continuous-mode PA operating in class-J mode.

In the continuation of the previous design, we developed two separate integrated GaN class-J MMICs with two different output-matching networks. The design goal was improved PA performance mainly in terms of the bandwidth and drain efficiency. The effect of the integrated inductor in compressing the bandwidth and degrading the efficiency was investigated by developing a hybrid output-matching network. As the required output power increases, the uncertainty in the nonlinear model used for simulation purpose rises. Therefore, we decided to obtain the required input and output impedances for the design requirements experimentally. For this purpose, we developed the on-wafer load-pull setup in iRadio lab. The setup consists of a microwave tuner at the source side and a harmonic and fundamental load tuners at the load side. We used a small thermal chuck to put the printed circuit board (PCB) containing an MMIC transistor on the probing station chuck. The mounting chuck had 4 tiny holes that connect to a vacuum pump, which provides enough suction to hold the PCB on the chuck during the measurement. Two GSG probes from Cascade are connected to the source and PHT tuners.

After the calibration of the probe station connected to load-pull system using network analyzer, a stabilized GaN MMIC transistor was used to design a single-ended PA by selecting appropriate input and output impedances for an input power of 18 dBm and a deep class-AB gate voltage of -4.2 V. The load-pull experiments were done at 2.14 GHz, 2.45 GHz and 2.5 GHz, which were selected since we have the second and third harmonic resonators of these frequencies. Our target for an integrated GaN PA was the generation of 1 watt and an efficiency higher than 50% across 1 GHz bandwidth from 1.8 GHz to 2.8 GHz. This bandwidth covers most of the high-band LTE signals. The class-J design space theory can predict the whole available space on the Smith chart that can provide the equal RF performance over a certain frequency bandwidth. Therefore, with the impedance results for three points on such a design space, we can tentatively predict the other impedance points on the Smith chart and design the required matching network circuits.

We designed a whole integrated class-J GaN PA based on the measured impedances from the on-wafer load-pull setup, and CMC fabricated 10 chips. Three chips were measured in the required input power in a continuous-wave test. The input power and frequency sweep measurements were done to evaluate the PA RF characteristics and the frequency response of the PA. The results showed good repeatability of the chip fabrication process by achieving almost similar output power, gain and efficiency responses over input power and frequency sweep. We measured an output power of 29 dBm and an efficiency higher than 50% from 1.85 GHz to 2.75 GHz, which satisfied the design requirements.

CMOS mm-wave PAs: The measured results for the fabricated 60 GHz complementary metal-oxide semiconductor (CMOS) amplifier were submitted as a conference paper and research is being conducted for other structures that are suitable for the mm-wave frequencies in CMOS technology for obtaining high efficiency at power back-off. It was shown through simulation that the proposed Doherty amplifier with three-port input/output networks is another solution for efficiency-optimized amplifiers in mmW frequencies.

One of the most bulky passive on-chip components is a splitter. It can take up approximately half of the chip, which can be a serious problem, especially in low frequencies. Modification of the design by removing this part from the circuit design can considerably alleviate this problem. A new splitter-less load-modulated PA was proposed last year. We designed the amplifier in 0.13 μm IBM CMOS technology. The amplifier was designed to work at 5.2 GHz and the output power at 24 dBm. The simulation results showed an efficiency of about 40% at the maximum output power, while the efficiency in 5 dB output power back-off (OPBO) was 30%. We recently received the chips, and measurements will soon be undertaken.

Millimetre-wave receiver: Another research thrust related to mm-wave communication is the unlicensed band from 57 GHz to 64 GHz (simply called the 60 GHz band), where new regulations demand R&D in mm-wave circuits and systems.

Our previous research works related to six-port based quadrature down-conversion successfully demonstrated an innovative design of wide-band, high-speed, low-cost and low-power wireless systems. The mm-wave technology can easily allow multi-Gb/s data rate in the 60 GHz band. A newly fabricated six-port receiver circuit in low-temperature co-fired ceramic (LTCC) technology for the 60 GHz communication band has been obtained, and all the relevant components have been mounted on it. New test equipment for 60 GHz measurements has been obtained, and the fabricated and assembled circuit's performance is being evaluated. This receiver front-end circuit will be used in conjunction with the DSP algorithms developed for single-band and multiband concurrent radio receiver applications using the six-port technique.

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) Chair proposal that covers April 2012 to March 2018. The overall long-term objective is the investigation of the scientific and technical problems related to software reconfigurable radio technology suitable for green broadband and ultra-wideband communications and for multi-standard and multimode handsets and base stations. This overall goal is divided into objectives specific to the research directions, which are listed in the following subsections.

Green SDR Transmitters

This research thrust focuses on the design of green software-defined radio (SDR) transmitters suitable for the next generations of wireless communication systems, including 5th generation (5G) wireless communication networks. Given the expectations that 5G systems will require substantial increases in bandwidth, the continuation of past

achievements in the modeling and design of switching-mode PAs (SMPAs) and radio systems will be focused on the development of new design approaches and methodologies that are able to achieve better or at least similar power efficiency over a large frequency band. Continuous-mode SMPAs, such as continuous-mode class-F, continuous-mode class-F⁻¹ and continuous-mode class-D SMPAs, will be one of the main focuses of research in this area.

While SMPAs offer excellent power efficiency at saturation, this efficiency degrades when using 4G+ and 5G signals with highly varying envelopes. Load modulation techniques will be used together with multi-harmonic tuning in SMPAs in order to maintain the high efficiency in the power back off. The investigation will include architectures such as multi-level pulse load modulation using SMPAs, harmonically tuned Doherty PAs, and harmonically tuned outphasing transmitters.

New broadband all-digital architectures that take advantage of power-efficient continuous-mode SMPAs will be proposed and implemented to ensure energy efficiency, flexibility/reconfigurability and linear operation over a wide frequency band. New topologies of wireless transmitters using mixer-less RFDACs (RF digital-to-analog converters) will offer solutions that are easily reconfigurable for wide frequency ranges, provide better linearity than state-of-the-art mixer-based solutions, reduce the power consumption compared to switching modulator based mixers, and ensure a higher dynamic range and higher linearity to meet the requirements of 5G wireless communication standards. Avoiding the use of filters along the up-conversion path will provide an overall transmitter solution that is easily integrable with a small footprint at a low cost. These are major features for the next generations of wireless communications, which will use massive MIMO (multiple input, multiple output) techniques.

Signal processing techniques, such as signal decomposition, noise shaping, noise reduction, linearization and equalization, will also be investigated for broadband signals; 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. The increasing bandwidth results in an increase in distortion and memory effects of the transmitter subsystems. Therefore, more stringent requirements are imposed on the complexity and speed of these signal-processing algorithms. New modeling and model optimization techniques will be sought in order to mitigate these challenges.

MIMO Radio Systems

To increase the spectrum efficiency and channel capacity in wireless transmissions, MIMO radio systems have been used over the last few years. New wireless communication standards are moving toward massive MIMO deployment in order to meet the demand for high data rates. This approach not only requires the design of low cost and integrable RF front-ends, but also puts stringent constraints on the design of the MIMO radio systems, in which the problems of crosstalk and linearity increase exponentially. New architectures based on MIMO systems will be proposed to address these challenges. These MIMO transceiver architectures will overcome the performance degradation in conventional MIMO systems, which are caused by the combined effect of components' impairments and the cross coupling between the transmitter and receiver branches, making the solution more suitable for massive MIMO implementation.

With the significant increase in system complexity and interaction between the different components in massive MIMO architectures and more stringent constraints imposed on data rates and energy efficiency of networks, it is inevitable that holistic approaches will be used to meet the needs targeted by the next generations of wireless communication standards. In this context, techniques for integrating and/or co-designing the PA along with the antenna array for massive MIMO systems will be proposed, in order to improve the integrability of the RF front-end and to reduce losses in the output matching networks of the PA, which will result in better overall power efficiency and optimized beam control.

Recently proposed DSP algorithms that shield MIMO radios from analog circuit impairments and problems triggered by the proximity of crosstalk between adjacent branches in MIMO radios require high computational complexity that increases exponentially with the number of branches in a MIMO system. Our work on the development of innovative

low-complexity algorithms and reduction of the complexity of existing solutions is important in making the implementation of these solutions possible for massive MIMO systems.

DSP for Wireless Communications

The predistortion of PAs and transmitters under wideband (100 MHz and more) drive signals is being pursued. One of the main limitations is largely due to the wide bandwidth of the observation path. Accordingly, particular emphasis will be given to proposing new signal acquisition techniques using sub-band sampling capable of broadening the observation window, while maintaining an acceptable dynamic range and signal quality. Moreover, conventional models that have been proposed for signals with narrower frequency bands will not be efficient or practical for use with signals that have a bandwidth of over 100 MHz. Indeed, such signals result in much higher and more complex nonlinear distortions and memory effects; and, more complex models with high nonlinearity and memory orders are required to obtain acceptable linearization quality. However, this type of model significantly increases the complexity of the baseband signal processing, making it impossible to implement at the high speeds required for such wideband applications. New model complexity reduction techniques, including pruning and compressive sensing, will be developed to increase the orders of nonlinearity and memory without increasing the overall complexity of the model. Low-complexity model identification techniques will also be investigated and proposed.

Another research topic in the DSP track is the design and development of energy-efficient transmitter architecture for concurrent multi-band and carrier aggregation (CA) in 4G+ (fourth generation and beyond) LTE-A wireless technology and the next generations of wireless communication standards. These standards consider the possibility of having simultaneous signal transmissions in multiple frequency bands by aggregating different carriers, in order to achieve high data rates and more efficient use of the frequency spectrum. The linearization of transmitter architectures supporting CA is of great importance to the realization of CA techniques. Indeed, due to either impractical sampling rate requirements of ADCs and DACs (analog-to-digital and digital-to-analog converters) required for these conventional digital predistortion (DPD) techniques or neglect of the cross-modulation effects between the multiple frequency carriers, conventional predistortion models are ineffective in addressing the linearity of carrier aggregated transmitters. New multiband linearization architectures that feature distortion compensation for the concurrent multiband transmitter will be developed. Reducing the complexity of multiband linearization techniques is another research aspect that will be investigated to make the generalization of the proposed linearization techniques from dual-band to tri-band and above possible and practical.

Green Adaptive and Tuneable Receivers

The 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, which will be able to effectively remove strong interference. 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 can 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. However, it has been proven that this technique increases the thermal noise and aggravates interference-related problems in receivers.

A second architecture for adaptive receivers consists of using a passive multiport 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. Dynamic linearization and calibration algorithms able to compensate for the frequency response and the dynamics have been investigated to enable UWB reception capabilities in the six-port receiver. These calibration algorithms allowed a signal-to-noise ratio (SNR) of about 30 dB for the received signals of a bandwidth higher than 10 MHz. Concurrent multi-standard reception using the six-port receiver has been investigated, and it has been shown

that the six-port topology is able to concurrently receive two different standards using the same hardware. Multi-standard calibration algorithms were also investigated and were proven to be able to reduce the distortion in the six-port receiver. The effectiveness of these algorithms in the presence of strong interference will be investigated. Modified and new calibration techniques and six-port topologies will be proposed to improve the selectivity of the concurrent band receiver in order to achieve better SNRs. Decreasing the complexity of the calibration procedure will ensure that the implementation of this technique for concurrent tri-band (and above) continues to have reasonable signal processing complexity.

The performance of these adaptive and tuneable receivers in the presence of strong interference is a serious challenge. Indeed, in order to ensure flexibility, these receiver are designed to work over a broad frequency band, which, when not carefully addressed, will result in poor selectivity and serious performance degradation due to interference. The performance of these tuneable receivers in the presence of strong interference will be assessed, and a technique to improve their selectivity will be proposed. In particular, impedance-mirroring techniques will be investigated in order to propose tuneable high selectivity for these flexible receivers without the use of bulky and lossy tuneable RF filters, which have poor selectivity.

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 multiband radio systems.	Professor Ghannouchi was selected as a Distinguished Speaker of IEEE-MTT-S for period of 2013-2014. 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 the Early Research Excellence Award from the Schulich School of Engineering (2013)
Dr. Abu Sesay	Professor Research interests include wireless communications	Dr. Sesay is associated with iRadio Lab
Dr. Abraham Fapojuwo	Professor Research interests include wireless networks	Dr. Fapojuwo is associated with iRadio Lab
Dr. L. Belostotski	Assistant professor Research interests include CMOS RFIC	Dr. Belostotski is associated with iRadio Lab

	transceivers design	
--	---------------------	--

VISITING PROFESSOR / RESEARCHERS		
Name	Role / Topic	Awards / Special Info
Dr. Mohammad S. Sharawi	MIMO Antenna Design	Assoc. Professor at King Fahd University of Petroleum and Minerals
Dr. Oualid Hammi	Mitigation of Power Amplifiers' Distortions Using Compressed Sensing Techniques	Assistant Professor at King Fahd University of Petroleum & Minerals

VISITING SPEAKERS		
Name	Topic	Special Info
Dr. Toshiyuki Yakabe	Six Port Network Analysis	Professor at The University of Electro-Communications, Tokyo, Japan
Dr. Mohammad S. Sharawi	Recent Advancements in Printed MIMO Antenna Design	Assoc. Professor at King Fahd University of Petroleum and Minerals

RESEARCH ASSOCIATES / ASSISTANTS		
Name	Role / Topic	Awards / Special Info
Suhas Illath Veetil	Research Assistant	
Neha Dawar	Research Assistant	

POSTDOCTORAL FELLOWS		
Name	Role / Topic	Awards / Special Info
Dr. Pouya Aflaki	Switching Mode PA Design for Delta-Sigma Transmitters	Mitacs
Dr. Ramzi Darraji	Wideband Doherty Power Amplifier Design	
Dr. Payam Dehghani Rahimzadeh	Energy Efficient Wireless Networks	Mitacs
Dr. Mohammadhassan Akbarpour	Digital Pre-Distortion for Concurrent Multiband and Multiple Antenna Transmission	Mitacs – Accelerate Graduate Research Internship Program
Dr. Saeed Rezaei Nazifi	All Digital, Multi-Standard Highly Efficient Transmitter for Mobile Communication Base Station Applications	Mitacs – Accelerate Graduate Research Internship Program
Dr. Mayada Younes	Behavioral Modeling and Digital Predistortion of Wireless Transmitters	

PHD CANDIDATES		
Name	Role / Topic	Awards / Special Info
Mohammadhassan Akbarpour	Broadband Power Amplifier Design	Supervised by Dr. F.M. Ghannouchi and Dr. M. Helaoui
Mohamed Ammar Al-Masri	Green Communication Networks	Supervised by Dr. Abu Sesay and Dr. Fadhel Ghannouchi
Mohsin Aziz	Compensation of Transmitter Impairments using Rational Functions	Supervised by Dr. Fadhel Ghannouchi
Fahmi Elsayed	Multi-level Delta Sigma Modulator Based Transmitters	Annual Progress Report Excellence Award, supervised by Dr. Mohamed Helaoui

Fatemeh Gohds	Dynamic Spectrum Allocation Techniques	Supervised by Dr. Abraham Fapojuwo and Dr. Fadhel Ghannouchi
Abul Hasan	60 GHz Multi-port Receivers	Annual Productivity Award, ECE Graduate Students Travel Award, Open Doctoral Scholarship Award, supervised by Dr. Mohamed Helaoui
Abubakr Hassan Abdelhafiz	Wideband Power Amplifier Characterization and Linearization	ECE Dept Award (Top 20 Student), Graduate Student Productivity Award, Best Research Abstract Award, supervised by Dr. Fadhel Ghannouchi
Maryam Jouzdani	Digital Transmitters using Pulse Load Modulation	ECE Special Scholarship Award, Graduate Student Productivity Award, supervised by Dr. Fadhel Ghannouchi
Andrew Kwan	Multi-band Envelope Tracking Transmitters	AITF Bill Bridger Award of Excellence, AITF Scholarship, Graduate Studies Travel Award, NSERC Alexander Graham Bell Graduate Scholarship – Doctoral, ECE Open Scholarship Award, supervised by Dr. Fadhel Ghannouchi
Xiang Li	Multi-Band Power Amplifier Design	Supervised by Dr. Mohamed Helaoui
Imen Mrissa	LTE Transceiver Design	Visiting Ph.D. student, INRS, Université du Québec
Saeed Rezaei Nazifi	Continuous Wave Power Amplifier Design	Supervised by Dr. Fadhel Ghannouchi and Dr. Leo Belostotski
Dimple Sharma	DVB Transceiver Design	Supervised by Dr. Fadhel Ghannouchi
Tushar Sharma	Digital Doherty Transmitters	Supervised by Dr. Fadhel Ghannouchi
Amir Vaezi	Visiting Grad Student – Amirkabir University	Supervised by Dr. Fadhel Ghannouchi

MSC CANDIDATES		
Name	Role / Topic	Awards / Special Info
Anis Ben Afri	MIMO Impairment Compensation	Graduate Student Productivity Award, supervised by Dr. Fadhel Ghannouchi
Mahmud Hasan	Frequency Based Predistortion of RF Power Amplifiers	Supervised by Dr. Fadhel Ghannouchi
Anis Messaoud	FPGA based Multi-band Predistortion	Supervised by Dr. Fadhel Ghannouchi
Piyush Rawat	RF Predistortion	Supervised by Dr. Mohamed Helaoui
Hosein Taghavi	CMOS PA Design	Research Productivity Award, supervised by Dr. Fadhel Ghannouchi
Milad Tajvidi	MIMO Antenna Beamforming	Supervised by Dr. Fadhel Ghannouchi
Suhas Illath Veetil	RF Digital to Analog Converters	Supervised by Dr. Mohamed Helaoui
Mike Wang	Wireless Channel Modeling	Supervised by Dr. Fadhel Ghannouchi
Gongzhe Su	Visiting Grad Student from Tsinghua University	Supervised by Dr. Fadhel Ghannouchi

OTHER TEAM MEMBERS (ASSOCIATES, UNDERGRADUATE STUDENTS, SUPPORT STAFF)	
Name	Role / Topic
Abul Hasan	Lab Manager
Andrew Kwan	Lab Manager

Chris Simon	Technical support
Caron Currie	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. 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.
Université de Québec: Dr. A. Kouki	The ongoing theme of collaboration is related to LINC-based amplifiers and GaN transistor modeling.
International Collaborations	
Participants	Nature of Collaboration
New York Institute of Technology Dr. Donglin Wang	The ongoing collaboration is related to indoor wireless location and positioning.
Tsinghua University, China Dr. Wenhua Chen	The ongoing collaboration is related to multiband transmitters design and linearization.
Indian Institute of Technologies Dr. Mohamad S. Hashmi	The ongoing collaboration is related to waveform engineering in amplifier design.
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. 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. Fadhel Ghannouchi is co-supervising the work of three Ph.D. candidates.
Hail University, KSA Dr. N. Boulejfene	The ongoing collaboration is related to behaviour modeling of wireless transmitters.
King Fahd University of Petroleum and Minerals Dr. Oualid Hammi	The ongoing collaboration is related to linearization of wireless transmitters.
Ningbo University, China Prof. T. Liu	The 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	The ongoing research activities are related to the design of dual-band Doherty PAs.
Tampere University of Technology, Tampere, Finland Dr. Mikko Valkama	Collaboration was initiated this year. Ongoing research activities are related to reducing complexity in digital predistortion techniques.
Amirkabir University, Iran Prof. A. Mohammadi	The ongoing research activities are related to six-port receivers and MIMO wireless systems.

7. GRADUATES

PH.D. Graduates			
Name	Degree	Research Topic	Current Position
Fahmi El-Sayed	PhD	Design of Delta-Sigma Wireless	Assistant Professor at Zagazig

		Receivers (Co-Supervised with M. Helaoui)	University Egypt
Saeed Rezaei Nazifi	PhD	Continuous-Mode Power Amplifiers for Broadband Power-Efficient Wireless Applications	PDF at University of Calgary
Mayada Younes	PhD	Behavioral Modeling and Digital Predistortion of Wireless Transmitters	PDF at University of Calgary
Mohammadhassan Akbarpour	PhD	Broadband and Energy-Efficient Power Amplifier Architectures	PDF at University of Calgary

M.Sc. Graduates			
Name	Degree	Research Topic	Current Position
Suhas Illath Veetil	MSc	RF Digital to Analog Converters	Research Assistant iRadio Lab
Piyush Rawat	MSc	Digital Pre-Distortion and Different Polynomial Models for Better Behavioral Modelling	NA

8. INTELLECTUAL PROPERTY

Patents and Patent Applications

1. F. M. Ghannouchi and M. A. Vejdani, "System and Method For Enhanced Transmitter Efficiency", US Patent Application 1463331375, filed 25 February 2015.
2. F. M. Ghannouchi, S. A. Bassam, M. Helaoui and R. Darraji, "Extended Bandwidth Digital Doherty Transmitter", China Patent Application PCT/CA2013/000678, filed 20 February 2015.
3. F. M. Ghannouchi, S. A. Bassam, M. Helaoui and R. Darraji, "Extended Bandwidth Digital Doherty Transmitter", Swedish Patent Application 1550180-2, filed 18 February 2015.
4. F. Elsayed, M. Helaoui, F. M. Ghannouchi, M. M. Ebrahimi and B. Morris, "Level De-multiplexed Sigma Delta Modulator Based Transmitter", US Patent Application US20150036766 A1, filed 5 February 2015.
5. F. M. Ghannouchi, S. A. Bassam, M. Helaoui and R. Darraji, "Extended Bandwidth Digital Doherty Transmitter", US Patent Application 20150010100 A1, filed 8 January 2015.
6. F. M. Ghannouchi, S. A. Bassam and M. Helaoui, "Multi-Cell Processing Architectures for Modeling and Impairment Compensation in Multi-Input Multi-output Systems," US Patent Application 20140301503 A1, filed 9 October 2014.
7. F. M. Ghannouchi, S. Bensmida, M. Hashmi and M. Helaoui, "Passive source and load-pull architecture for high reflection factor synthesis", US Patent 8,841,922, 23 September 2014.
8. F. M. Ghannouchi and R. Darraji, "Extended Bandwidth Digital Doherty Transmitter", US Patent 8,837,629, 16 September 2014.
9. 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 8,817,859, 26 August 2014.
10. F. M. Ghannouchi, M. Helaoui, S. Hatami and R. Negra, "All-Digital Multi-standard Transmitter Architecture using Sigma-Delta Modulators", US Patent Application 20140211886 A1, filed 31 July 2014.
11. 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 8,767,857, 1 July 2014.

12. M. M. Ebrahimi, M. Helaoui, F. M. Ghannouchi, F. Elsayed and B. Morris, "ACPR Enhanced Complex Delta Sigma Modulator Transmitter", PCT Patent Application PCT/IB2014/062544, filed 23 June 2014.
13. F. M. Ghannouchi, M. Helaoui, S. Hatami and R. Negra, "All-Digital Multi-standard Transmitter Architecture using Sigma-Delta Modulators", US Patent 8,724,733, 13 May 2014.

9. PUBLICATIONS

Refereed Journal Publications

1. M. Younes and F. M. Ghannouchi, "Behavioral Modeling of Concurrent Dual-band Transmitters based on Radial-Pruned Volterra Model", IEEE Communication Letters, 2015, accepted.
2. R. Darraji, A. K. Kwan, F. M. Ghannouchi and M. Helaoui, "Digitally Equalized Doherty RF Front-End Architecture for Broadband and Multistandard Wireless Transmitters", IEEE Transactions on Microwave Theory and Techniques, 2015, accepted.
3. M. Jouzdani, M. M. Ebrahimi, K. Rawat, M. Helaoui and F. M. Ghannouchi, "Envelope Tracked Pulse Gate Modulated GaN HEMT Power Amplifier for Wireless Transmitters", IEEE Transactions on Circuits and Systems I, Vol. 62: Issue 2, pp. 571-579, February 2015.
4. A. Seregin, O. Hammi, D. Wang, M. Helaoui and F. Ghannouchi, "Modified Linear Prediction Algorithm for Narrowband Interference Suppression in Universal Mobile Telecommunication System", Wireless Communications and Mobile Computing, Vol. 15: Issue 1, pp. 147-154, January 2015.
5. S. Rezaei, L. Belostotski, M. Helaoui and F. M. Ghannouchi, "Harmonically Tuned Continuous Class C Operation Mode for Power Amplifier Applications", IEEE Transactions on Microwave Theory and Techniques, Vol. 62: Issue 12, pp. 3017-3027, December 2014.
6. A. K. Kwan, M. Younes, F. M. Ghannouchi, S. Zhang, W. Chen, R. Darraji, M. Helaoui and O. Hammi, "Concurrent Multi-Band Envelope Modulated Power Amplifier Linearized Using Extended Phase-Aligned DPD", IEEE Transactions on Microwave Theory and Techniques, Vol. 62: Issue 12, pp. 3298-3308, December 2014.
7. O. Hammi, A. Kwan, S. Bensmida, K. A. Morris and F. M. Ghannouchi, "A Digital Predistortion System with Extended Correction Bandwidth with Application to LTE-A Nonlinear Power Amplifiers", IEEE Transactions on Circuits and Systems I: Regular Papers, Vol. 61: Issue 12, pp. 3487-3495, December 2014.
8. S. Tatu, A. Serban, M. Helaoui and A. Koelpin, "Multiport Technology: The New Rise of an Old Concept", IEEE Microwave Magazine, Vol. 15: Issue 7, pp. 34-44, November 2014.
9. A. Abdelhafiz, A. Zerguine, O. Hammi and F. M. Ghannouchi, "A Lattice-Based Memory Polynomial Predistorter for Wideband RF Power Amplifiers", IET Communications, Vol. 8: Issue 17, pp. 3122-3127, November 2014.
10. A. Abdelhafiz, A. Kwan, O. Hammi and F. M. Ghannouchi, "Digital Predistortion of LTE-A Power Amplifiers Using Compressed Sampling Based Unstructured Pruning of Volterra Series", IEEE Transactions on Microwave Theory and Techniques, Vol. 62: Issue 11, pp. 2583-2593, November 2014.
11. W. Chen, S. Zhang, Y.-J. Liu, F. M. Ghannouchi, Z. Feng and Y. Liu, "Efficient Pruning Technique of Memory Polynomial Models Suitable for PA Behavioral Modeling and Digital Predistortion", IEEE Transactions on Microwave Theory and Techniques, Vol. 62: Issue 10, pp. 2290-2299, October 2014.
12. M. Aziz, M. Rawat and F. M. Ghannouchi, "Low Complexity Distributed Model for the Compensation of Direct Conversion Transmitter's Imperfections", IEEE Transactions on Broadcasting, Vol. 60: Issue 3, pp. 568-574, September 2014.

13. M. Rawat, K. Rawat, R. Darraji, F. E. Alfaro, S. A. Bassam, M. Helaoui, F. M. Ghannouchi, M. Fattouche and F. Falcone, "Cooperative network solution and implementation for emergency applications with enhanced position estimation capability", *Wireless Networks*, Vol. 20: Issue 5, pp. 1157-1168, July 2014.
14. L. Azpilicueta, M. Rawat, K. Rawat, F. M. Ghannouchi and F. Falcone, "A Ray Launching-Neural Network Approach for Radio Wave Propagation Analysis in Complex Indoor Environments", *IEEE Transactions on Antennas and Propagation*, Vol. 62: Issue 5, pp. 2777-2786, May 2014.
15. J. R. G. Oya, A. Kwan, F. M. Ghannouchi, S. A. Bassam and F. M. Chavero, "Design of Dual-Band Multistandard Subsampling Receivers for Optimal SNDR in Nonlinear and Interfering Environments", *IEEE Transactions on Instrumentation and Measurement*, Vol. 63: Issue 4, pp. 981-983, April 2014.
16. S. Hatami, M. Helaoui, F. M. Ghannouchi and M. Pedram, "Single-Bit Pseudoparallel Processing Low-Oversampling Delta-Sigma Modulator Suitable for SDR Wireless Transmitters", *IEEE Transactions on Very Large Scale Integration Systems*, Vol. 22: Issue 4, pp. 922-931, April 2014.
17. L. Azpilicueta, M. Rawat, K. Rawat, F. M. Ghannouchi and F. Falcone, "Convergence Analysis in Deterministic 3D Ray Launching Radio Channel Estimation in Complex Environments", *Applied Computational Electromagnetics Society Journal*, Vol. 29: Issue 4, pp. 256-271, April 2014.

Refereed Conference Proceedings

1. M. Jouzdani and F. M. Ghannouchi, "High Efficiency Delta-Sigma Transmitter Architecture with Gate Bias Modulation for Wireless Applications", 58th IEEE International Midwest Symposium on Circuits & Systems (MWSCAS'2015), Fort Collins, CO, USA, 2-5 August 2015, accepted.
2. A. Abdelhafiz, O. Hammi and F. M. Ghannouchi, "A Lattice-based Memory Polynomial Behavioral Model for Nonlinear MIMO Transmitters Using Fixed Point Arithmetic", 2015 IEEE MTT-S International Microwave Symposium (IMS'2015), Phoenix, AZ, USA, 17-22 May 2015, accepted.
3. A. Ben Arfi, M. Helaoui and F. M. Ghannouchi, "All-digital Sigma-Delta RF Modulator for Software Defined Radio Applications", 2015 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2015), Halifax, NS, Canada, 3-6 May 2015.
4. M. Khalifa, A. Abdelhafiz, A. Kwan, F. M. Ghannouchi and O. Hammi, "Behavioral Modeling of Envelope Tracking Power Amplifier using Volterra Series Model and Compressed Sampling", 2015 IEEE International Wireless Symposium (IWS'2015), Shenzhen, China, 30 March - 1 April 2015.
5. A. Abdelhafiz, M. Younes, A. Kwan, O. Hammi, F. M. Ghannouchi and N. Boulejfen, "A Comparative Study of Wideband and Dual-Band Digital Predistortion Architectures", IWS'2015, Shenzhen, China, 30 March - 1 April 2015.
6. M. Vejdaniamiri, M. Helaoui and F. M. Ghannouchi, "On the Estimation of Power Amplifier Efficiency for Modulated Signals", 2015 IEEE Radio and Wireless Symposium (RWS'2015), San Diego, CA, USA, 25-28 January 2015.
7. A. Hasan, M. Helaoui, N. Boulejfen and F. M. Ghannouchi, "Six-Port Technology for MIMO and Cognitive Radio Receiver Applications", RWS'2015, San Diego, CA, USA, 25 - 28 January 2015.
8. M. A. Maktoomi, V. Panwar, M. S. Hashmi and F. M. Ghannouchi, "A Dual-Band Matching Network for Frequency-Dependent Complex Loads Suitable for Dual-Band RF Amplifiers" 2014 IEEE MTT-S International Microwave and RF Conference (IMaRC'2014), Bangalore, India, pp. 88-91, 15-17 December 2014.
9. H. Taghavi, M. Akbarpour, S. Rezaei and F. M. Ghannouchi, "Broadband High Efficiency GaN RF Power Amplifier for Multi-Band Applications", 14th Mediterranean Microwave Symposium (MMS'2014), Marrakech, Morocco, 12-14 December 2014.

10. T. Sharma, R. Darraji and F. M. Ghannouchi, "High Efficiency Continuous Mode Power Amplifiers using Waveform Engineering", MMS'2014, Marrakech, Morocco, 12-14 December 2014.
11. A. Ben Arfi, F. M. Ghannouchi, R. Barrak and C. Rebai, "A GNSS Receiver Using Band-pass Continuous-time Delta-sigma Modulator", MMS'2014, Marrakech, Morocco, 12-14 December 2014.
12. T. Sharma, R. Darraji and F. M. Ghannouchi, "Design Methodology of High Efficiency Continuous Mode Transfer Power Amplifiers with One Octave Bandwidth", 21st IEEE International Conference on Electronics Circuits and Systems (ICECS'2014), Marseille, France, pp. 674-677, 7-10 December 2014.
13. F. M. Ghannouchi, A. K. Kwan, M. Younes and W. Chen, "DSP Techniques for Linearity and Efficiency Enhancement of Multi-band Envelope Tracking Transmitters (Invited Paper)", 2014 Asia-Pacific Microwave Conference (APMC'2014), Sendai, Japan, pp. 1082-1084, 4-7 November 2014.
14. S. I. Veetil and M. Helaoui, "Signal Conditioning for Polar All-Digital OFDM Wireless Transmitters", 10th IEEE Dallas Circuits and Systems Conference (DCAS'2014), Dallas, TX, USA, 12-13 October 2014.
15. A. Olopade and M. Helaoui, "Mitigation of Distortion and Memory Effect in a Concurrent Dual-band Six Port Receivers", 44th European Microwave Conference (EuMC'2014), Rome, Italy, pp. 1138-1141, 5-10 October 2014.
16. F. Elsayed, M. Helaoui and F. M. Ghannouchi, "Effect of the Level Values of Three-Level EDSM on The Efficiency of Overall Transmitter", 9th European Microwave Integrated Circuits Conference (EuMIC'2014), Rome, Italy, 5-10 October 2014.
17. A. Zerguine, O. Hammi, A. Abdelhafiz and F. M. Ghannouchi, "A Predistorter Based on the Least-Mean Squares Newton Algorithm", 2014 International Symposium on Nonlinear Theory and its Applications (NOLTA'2014), Luzern, Switzerland, 14-18 September 2014.
18. R. Darraji and F. M. Ghannouchi, "Analysis of the Impact of Finite Off-State Impedance of Peaking Branch on the Efficiency of Doherty Amplifiers", 12th IEEE International New Circuits and Systems Conference (NEWCAS'2014), Trois-Rivières, QC, Canada, pp. 269-272, 22-25 June 2014.
19. G. Su, W. Chen, S. Zhang and F. M. Ghannouchi, "A robust and low sampling rate digital predistortion algorithm for broadband PA modeling and predistortion", 15th IEEE Annual Wireless and Microwave Technology Conference (WAMICON'2014), Tampa Bay, FL, USA, 6 June 2014.
20. K. Rawat, B. Gowrish, G. Ajmera, R. Kalyan, A. Basu, S. Koul and F. M. Ghannouchi, "Design strategy for tri-band Doherty power amplifier", WAMICON'2014, Tampa Bay, FL, USA, 6 June 2014.
21. M. Abdelaziz, L. Anttila, J. R. Cavallaro, S. S. Bhattacharyya, A. Mohammadi, F. M. Ghannouchi, M. Juntti and M. Valkama, "Low-complexity digital predistortion for reducing power amplifier spurious emissions in spectrally-agile flexible radio", 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM'2014), Oulu, Finland, pp. 323-328, 2-4 June 2014.
22. A. K. Kwan, M. Younes, S. Zhang, W. Chen, R. Darraji, M. Helaoui and F. M. Ghannouchi, "Dual-band Predistortion Linearization of an Envelope Modulated Power Amplifier Operated in Concurrent Multi-Standard Mode", 2014 IEEE MTT-S International Microwave Symposium (IMS'2014), Tampa Bay, FL, USA, 1-6 June 2014.
23. F. M. Elsayed, M. M. Ebrahimi, M. Helaoui and F. M. Ghannouchi, "Linear and Efficient Multi-Level Polar Delta-Sigma Modulator Based Transmitter", in 2014 IEEE MTT-S International Microwave Symposium (IMS'2014), Tampa Bay, FL, USA, 1-6 June 2014.
24. X. Chen, W. Chen, G. Su, Z. Feng and F. M. Ghannouchi, "A Concurrent Dual-band 1.9-2.6-GHz Doherty Power Amplifier with Intermodulation Impedance Tuning", IMS'2014, Tampa Bay, FL, USA, 1-6 June 2014.
25. M. Younes, A. Kwan and F. M. Ghannouchi, "Digital Predistortion of Concurrent Dual-Band Power Amplifier based on Two-dimensional Multi-Branch DPD", 2014 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2014), Toronto, ON, Canada, 4-7 May 2014.

26. A. O. Olopade and M. Helaoui, "High Performance Homodyne Six Port Receiver using Memory Polynomial Calibration", CCECE'2014, Toronto, ON, Canada, 4-7 May 2014.
27. M. A. Messaoud, R. Barrak and F. M. Ghannouchi, "Optimized Subsampling Frequency Selection for Nonlinear Systems", CCECE'2014, Toronto, ON, Canada, 4-7 May 2014.
28. M. Jouzdani, M. M. Ebrahimi and F. M. Ghannouchi, "GaN Polar Transmitter Design for Base-station Applications", CCECE'2014, Toronto, ON, Canada, 4-7 May 2014.
29. F. Elsayed, M. Ebrahimi, M. Helaoui and F. M. Ghannouchi, "First- and Second-Order Envelope DSM Circuits", CCECE'2014, Toronto, ON, Canada, 4-7 May 2014.
30. M. Abdelaziz, L. Anttila, A. Mohammadi, F. M. Ghannouchi and M. Valkama, "Reduced-Complexity Power Amplifier Linearization for Carrier Aggregation Mobile Transceivers", 2014 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP'2014), Florence, Italy, pp. 3908-3912, 4-9 May 2014.
31. W. Chen, X. Chen, G. Su, S. Zhang and F. M. Ghannouchi, "Advanced power amplifier technologies for multistandard and broadband wireless communications", 2014 International Workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC'2014), Leuven, Belgium, 2-4 April 2014.

Books and Book Chapters

1. M Akbarpour, F. M. Ghannouchi and M. Helaoui, "mmW Doherty" in *Linearization and Efficiency Enhancement Techniques for Silicon Power Amplifiers: From RF to mmW*, Academic Press, 2015.
2. F. M. Ghannouchi, O. Hammi and M. Helaoui, "Digital Predistortion for Microwave Transmitters" in *Wiley Encyclopedia of Electrical and Electronics Engineering*, Wiley, 2014.

Special/Invited Presentations:

1. Professor F. M. Ghannouchi gave an invited talk, entitled "DSP Techniques for Linearity and Efficiency Enhancement of Multi-band Envelope Tracking Transmitters", at the Asia Pacific Microwave Conference (APMC'2014) on November 7, 2014
2. Professor F. M. Ghannouchi gave an invited talk, entitled "Advanced amplifiers and Transmitters for Software Defined Applications", at University of Leuven, Belgium on July, 10, 2014.
3. Professor F. M. Ghannouchi, as a Distinguished Microwave Lecturer gave an invited talk, entitled "All Digital Transmitters for Next Generation of Wireless communications", at University of Paris Est, Marne-la-Vallee, ESIEE, on July 8, 2014.

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 iRadio Lab hosted the University of Calgary booth at the 2013 IEEE International Microwave Symposium (IMS'2013), held in Seattle, WA, USA. Among the demonstrations of lab activities, two innovative PA design prototypes were revealed to industry and academic colleagues.

The iRadio Lab group is also active within the Department of Electrical and Computer Engineering at the University of Calgary. Some members are prominent in the ECE graduate student society, promoting outreach activities for graduate students. Another member presented a lecture and gave a hands-on education activity demonstrating radio emissions produced by the sun, planets and a galaxy, sponsored by the IEEE student branch. Selected members are also active in judging the Schulich School of Engineering 4th-year capstone fair, evaluating projects across all disciplines of engineering.

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 this year. This spreadsheet is attached to this report. Funding sources included:

- AITF, 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

