iRadio Laboratory Annual Report
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1. EXECUTIVE SUMMARY

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

iRadio Lab is already staffed with more than twenty graduate students and talented researchers, who have been recruited worldwide. The main space dedicated to iRadio Lab in the University of Calgary's ICT building (ICT 305 and ICT 318) 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) is also being utilized by graduate students and researchers for printed circuit board fabrication and prototyping. iRadio Lab's facilities are supported by a number of test benches and rapid prototyping setups and by computer-aided design (CAD) based software. During the last year, iRadio Lab started the process of the procurement a new mm-wave measurement and prototyping facility with a total value of over a million dollar thanks to a set of grants from Canada Foundation for Innovation (CFI), Alberta Enterprise and Advanced Education (AEAE) and equipment providers. This new facility is composed of the latest and state-of-the-art measurement equipment and offers the capabilities of ultra-wideband measurement (up to 2 GHz bandwidth modulated signals) at mm-wave frequencies (up to 67 GHz), which are unique in Alberta and Canada.

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 have led to forty-five (45) refereed journal papers (published and accepted), twenty (20) refereed conference papers (published and accepted), two patent applications and the publication of one book and one book chapters. Nine keynote and invited talks were given by iRadio Lab researchers at international conferences and leading research institutions and universities. A Ph.D. student, Saeed Rezaei, was awarded the Killam scholarship; and, a second Ph.D. student, Ramzi Darraji, was the recipient of the best paper prize at an international conference. One of our papers published in *IEEE Systems Journal* was among the top 25 downloaded papers.

During its eight year, iRadio Lab was successful in securing substantial funding: $160K from the Natural Sciences and Engineering Research Council of Canada (NSERC), $460K from CFI, $380K from AEAE and $123K from industry. These monies supplement the $850K, $200K and $150K yearly averages provided by AITF, the Canada Research Chairs (CRC) program and the University of Calgary, respectively. In addition, in-kind contributions and equipment donation in the amounts of about $330K from industry partners and $200K of in-kind contributions from the University of Calgary have been obtained during the reporting period. Furthermore, many students have been awarded scholarships and fellowships over the last year, totalling an annual average of $135K.

2. RESEARCH PROGRAM OVERVIEW

The Research Team

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

Research Partners

iRadio Lab has been mainly funded by joint sponsorship from 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 in the following areas:

i. Semiconductor technology (Cree and Canadian Microelectronics Corporation),

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

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

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) and mixed signal technology, microwave and mm-wave technology, and communications systems, including the manufacturing processes and implementation in the respective fields. The ongoing research activities span over the following research directions that were identified in the original research proposal.

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

Green microwave: 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.

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.

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.

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 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.

All the current and planned activities of iRadio Lab are in line with the aforementioned research directions. These projects all serve the intention of the research proposal submitted to AITF, which was aimed at the development and advancement of knowledge and know-how related to the design of intelligent and reconfigurable RF front-ends for green, multi-standard, broadband communication systems. The optimization of power-added efficiency, due mainly to the reduction in DC power consumption of RF radios, is one of the objectives of the research program, as initially stated in the chair proposal; and, since it may favourably impact the environment, this research thrust is being branded as green RF electronics, to better reflect its importance to the nontechnical person and to society at large.

3. RESEARCH 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 initial goalsstated in the Chair research proposal..

Microwave and Radio Frequency (RF) Device Characterization and Modeling

GaN HEMT modeling: Gallium nitride (GaN) high-electron mobility transistors (HEMTs) are able to generate high-output power, good linearity, high power efficiency and low self-heating at microwave frequencies. For these reasons, GaN transistors are the superior choice for microwave switching-mode power amplifier (PA) design. Switching-mode

PAs can theoretically achieve 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 PA performance, a simple switch-based model was introduced to predict the behavior 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, further modifications and studies have been continued during the past year, in close collaboration with academia (École de Technologie Supérieure (ETS), Université du Québec) and industrial partners (National Research Council Canada, NRC, and Canadian Microelectronics Corporation, CMC).

Broadband switching-mode PAs have recently captured a lot of attention due to their suitability for multiband, multi-standard transmitters, such as polar, envelope-tracking or delta-sigma based transmitters. Two approaches for the design of such PAs for multiband transmitting systems can be adopted. If the frequency bands of the system are not very close, the multiband PA can be designed with quasi-optimal performance. However, if the frequency bands of the system are adjacent, a broadband PA design is preferred to cover the whole frequency band.

In broadband switching-mode PAs, both fundamental and harmonic frequencies should be considered for the design of the matching network for the whole desired bandwidth. In such a case, the two or three-component matching networks often needed for narrowband design have to be replaced by more complex matching networks with relatively high numbers of components. This often results in increases of the insertion losses in the matching networks and of the sensitivity of the design to the components' tolerance. Accordingly, a very precise comprehensive design procedure was developed to design and synthesize a reasonably complex broadband matching network for the switching-mode PA. A proof-of-concept, wideband, class-E, switching-mode PA design was carried out, and high bandwidth was obtained by moving from a four-component narrowband low-pass matching network to a ten-component broadband bandpass matching network. The bandwidth of the 2 GHz PA was extended from 400 MHz with 60% efficiency to 700 MHz while maintaining the same efficiency.

Continuous-mode PAs have recently attracted a lot of attention, due to their suitability for broadband single-stage PA design. The intrinsic drain voltage of the transistor can be manipulated in a way that creates a set of intrinsic drain

voltage and current waveforms with variable magnitudes that provide identical output power, gain and drain efficiency at the PA output. This manipulation can be achieved by properly setting the fundamental and harmonic impedances presented to the transistor intrinsic current source. Therefore, loci of fundamental and harmonic impedances on the Smith chart that provide the same performance can be defined and are called design spaces. By mapping each point on the design space to a single frequency point, a broadband PA with optimal performance can be easily designed with a low-complexity, output-matching network. Based on this concept, a continuous-mode GaN PA design project has been carried out during the last year. The world's first integrated continuous-mode PA operating in class-J mode was designed and fabricated using the services of Canada Microelectronic Corporation (CMC). As anticipated by the theory and CAD simulations, the measured broadband output power (1 Watt) and power efficiency (70%) performance covered the 1 GHz frequency bandwidth centred around 2.5 GHz.

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

Green RF Power Amplification Systems

The objective of this research project is the design of energy efficient (green) and broadband PAs/transmitters for wireless communication standards (third generation and beyond). The activities carried out within this project have been initiated and performed in close collaboration with the Canadian Space Agency (CSA), CMC and University du Québec in Montréal.

In continuation of work done in the previous year on the design of broad bandwidth, digitally driven Doherty PAs, a new digitally equalized Doherty PA based RF front-end architecture was proposed and successfully tested in the context of broadband and concurrent multi-standard applications. The proposed architecture incorporates a baseband equalizer that is implemented using finite impulse response (FIR) digital filters to improve the performance of Doherty PAs when driven with large bandwidth and multiband wireless radios. Depending on the centre frequency and bandwidth of the input signal, the FIR filters of the baseband equalizer are synthesized to compensate for the non-ideal frequency behaviour of the RF building blocks of the Doherty PA, thereby boosting its bandwidth efficiency. Furthermore, the baseband equalizer enables the Doherty PA to operate efficiently beyond its nominal frequency band, which is suitable for multi-standard applications. When driven with a 60-MHz bandwidth Long-Term Evolution (LTE) signal, the average efficiency of a Doherty PA prototype allied with the proposed digital baseband equalizer was improved from 36.9% to 42.5% for nearly identical performances in terms of output power and linearity. Moreover, when operated in a concurrent dual-band mode with two 20-MHz bandwidth LTE signals, the proposed Doherty PA enabled a reduction in DC power consumption by nearly 15%.

In another research project, a new structure, denoted as a transformer-less load modulated (TLLM) amplifier, was proposed to enable high-efficiency operation over large frequency bandwidth without application of digital processing techniques. The TLLM amplifier has the same efficiency as the Doherty amplifier; however, since it does not use the impedance inverters and offset lines of the Doherty amplifier, the TLLM amplifier presents high efficiency in a larger frequency band than the Doherty amplifier. A 10-Watt prototype of the TLLM amplifier was fabricated and successfully tested in a frequency band of 1.95 – 2.45 GHz. Since the TLLM amplifier utilizes a minimum number of elements at its output, it is suitable for mm-wave designs, where the lower number of elements leads to lower loss and, consequently, higher amplifier efficiency. A 60-GHz TLLM amplifier was designed and fabricated in 65-nm CMOS (complementary metal-oxide semiconductor) technology. The test results showed the best achieved performance so far for 60-GHz CMOS amplifiers in the open literature.

Another novel amplifier structure was also proposed and demonstrated to be capable of producing high efficiency for complex modulated signals throughout a very large frequency bandwidth. The test results on a prototype of this amplifier showed more than an efficiency of 40% for a WiMAX (Worldwide Interoperability for Microwave Access) signal over 2 octaves (500 MHz – 2 GHz) of frequency bandwidth.

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

Advanced Adaptive DSP Algorithms for Wireless Transceivers

Many factors affect the signal quality and efficiency of wireless transceivers in the RF/analog domain. The complexity of this problem increases exponentially when increasing the signal bandwidth or considering multiple input, multiple output (MIMO) systems. Instead of compensating for these imperfections using restrictive analog components, flexibility can be achieved using unique digital signal processing (DSP) algorithms implemented on a baseband processor.

MIMO transmitter nonlinear behavioural models require, in most cases, a high polynomial order and a large memory depth to accurately mimic their nonlinear dynamic characteristics, which are needed for digital predistortion (DPD) applications that improve their power efficiency. A recent trend is the elimination of some of these orders to reduce software implementation complexity of signal processors. Research was conducted on the analysis of the information characteristics of the transmitted signal for order elimination. The results obtained show that, for different configurations (SISO and MIMO transmitter architectures) and RF operating frequencies, the reduced model is able to provide the same linearization performance, while reducing complexity by approximately 50%.

Transmitter hardware impairments deteriorate signal quality and may introduce spectral interference with nearby frequency channels. In a traditional transmitter, calibration of the modulator is typically done before compensation of nonlinearities in the PA and independently of the predistortion. Joint modeling and compensation for the modulator and PA nonlinearity can reduce RF hardware components and decrease the time spent calibrating the transmitter system. Both neural network and Volterra-based models were developed for this proposed architecture and showed excellent performance in modeling and compensating for these imperfections. A generalized twin-box model was proposed for the mutual compensation of the PA nonlinearities and RF impairments in the direct conversion transmitter. The proposed DPD was tested for both homodyne and heterodyne transmitters and showed significant improvement in the image rejection ratio.

Wireless localization and positioning of mobile devices are important for a variety of applications. During the last year, a project was launched to study and propose a wireless localization and positioning technique for emergency scenarios, such as wildfire firefighting, where limited or no cellular coverage can occur and make detection of a mobile users' position difficult. This is of great concern when these users are injured. The outcome of the project was a proposal of a network-based positioning system based on the deployment of mobile base stations, allowing the localization and positioning of intervening teams (firefighters, medical emergency personnel and police) to accurately determine real-time user positions in the field.

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

Adaptive and Tuneable Receivers

Many radio applications require the capture and decoding of multiple RF bands. Moreover, a nonlinear system results in a large number of frequency components when characterized for its nonlinearity. Synthesizing a receiver that can capture a large number of RF bands would be beneficial, but the implementation of circuitry or high-speed processing is difficult. Instead, allowing for adaptive and/or tuneable receivers provides radio systems with frequency flexibility. These receivers may be built using either wide bandwidth low-sampling analog-to-digital converters (ADCs) or multiport interferometer circuit based techniques.

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

The advantages of subsampling receivers can be shown in cognitive radio and amplifier linearization applications. In radios, wireless standards are imposed with a fixed frequency allocation where they must operate. Some of these frequency channels are used more than others, causing channel congestion where too many transmissions may interfere with each other. Cognitive radios aim to reduce these loads by spreading wireless traffic over several channels. A wideband receiver is required for these applications; however, if the bands are known, a low-speed high-bandwidth ADC is suggested to sense the underused channels and reduce costs. An optimized subsampling receiver architecture has been developed where, by using different clocks for sample-and-hold circuit, an ADC component and a bandpass filter bank, twelve different dual-band signals have been received with better SNR performance.

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

Ultra-wideband six-port based direct conversion receivers: The next part of this project focuses primarily on the use of the six-port technique for direct down-conversion of the RF signals to the baseband. Six-port networks are passive microwave circuits that are highly linear and can be designed to be ultra-wideband (UWB). The ongoing project on UWB signal down-conversion topology using a passive six-port network has seen interesting results. The use of only passive components not only reduces the power consumption in the receiver side, thereby increasing the battery life in mobile communications, but also allows for the design of a UWB receiver that can be used for multi-standard and multicarrier frequencies. In addition, this topology is highly linear and, thus, eliminates the nonlinear distortions introduced by conventional diode-based mixers. A prototype of the UWB receiver (2 GHz – 18 GHz) has been assembled and tested at different frequencies for single-band and dual-band WiMAX and LTE-Advanced applications. A comparative analysis of linear six-port calibration techniques has been done, and the proposed calibration approach for six-port has been found to be the best among the state-of-art calibration techniques.

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

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

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

SDR Transmitters

In a software-defined radio (SDR), the radio platform is reconfigurable by software, allowing for the possibility of switching between different standards. One interesting architecture solution for SDR is the implementation and use of an all-digital transmitter, where all blocks are implemented in the digital domain. This digital implementation is characterized by its flexibility, reconfigurability and reprogrammability, which are suitable for multiband and multi-standard applications.

The all-digital transmitter project investigates the design of an RF wireless transmitter using digital components that is reconfigurable and adaptable to several communication standards. The heart of the digital transmitter is a delta-sigma modulator (DSM), which transforms a varying-envelope signal to a constant-envelope signal, in order to be able to use a highly efficient switching-mode PA. Two approaches for designing a programmable all-digital transmitter platform for SDR applications were studied and implemented. In one approach, the DSM was directly driven by the signal; and, its output, which had both phase and amplitude information of the original signal, was used to feed the PA. In another approach, only the envelope of the signal was fed to the input of the DSM. This DSM quantizes the envelope signal, which is used to modulate the gate bias of the transistor. The phase information from the original signal is supplied to the input of the PA as a constant-envelope signal.

Multilevel delta-sigma based transmitters: Implementation and validation of wideband DSMs for GHz frequency applications have been made possible with parallel processing techniques and high-speed multiplexers. However, the power efficiency of these architectures tends to be relatively low. Multilevel delta-sigma modulation is a promising solution for the enhancement of power efficiency of such transmitters, and it has been investigated during the last year. This study led to the proposal of a new delta-sigma architecture based on a multilevel quantization scheme, and simulation and measurement results have shown its potential in achieving high efficiency. Multilevel delta-sigma-based transmitter architecture was fully designed and measured; and, the transmitter showed good linearity and efficiency with a considerable decrease in the complexity of the transmitter when a discrete-level gain adjustment (DLGA) algorithm was utilized instead of using fully digital predistortion.

In order to further enhance the transmitted signal fidelity and improve the transmitter efficiency, a level demultiplexed multilevel DSM transmitter architecture was designed. The design was based on two switching-mode PAs connected together by a T-junction transmission line, which acts as a combiner. The preliminary measurement results show promising performance, in terms of energy efficiency and linearity. Moreover, since this topology does not use power combiners, the bandwidth of the architecture can be extended to serve multi-standard applications.

Performance enhancement in delta-sigma based transmitters: The efficiency and bandwidth enhancement of delta-sigma based transmitters have also been addressed in our recent research. While the constant-envelope signal enables the utilization of highly efficient switching-mode PAs, the presence of quantization noise limits the maximum achievable bandwidth and efficiency of the transmitters. In addition to the application of multilevel quantization in DSMs to reduce the quantization noise, some signal processing techniques have been implemented to improve both the efficiency and bandwidth of the DSM based transmitters. In one approach, a portion of the quantization noise (in-band and out-of-band) is removed to improve the efficiency and decrease the oversampling ratio (or increase the bandwidth). In another technique, the Cartesian DSM is replaced by a complex DSM, which considerably reduces the quantization noise of the DSM, while maintaining a constant envelope of the output signal from the DSM.

Pulse load modulation (PLM) transmitters: Digital modulation schemes, such as LTE and WCDMA (wideband code division multiple access), used in modern cellular communication systems result in signals with high peak-to-average power ratios. These systems require PAs with superior performance. To avoid spectral spreading, the PAs used in such systems should be operated efficiently at large back-off power levels. One promising solution to enhance the efficiency of PAs at high back-off powers is the modulation of the load impedance of the amplifier according to the output power levels. The efficiency of PAs in back-off power regions can be improved with the use of a new structure called a pulsed load modulation (PLM) PA, which is based on digital load modulation. The PLM amplifier structure consists of two class-B PAs and a high-Q band-pass filter. In this amplifier, the impedance at the output of the two PAs or input of the bandpass filter varies automatically for different power levels.

In this project, a PLM-based PA using 10-Watt GaN technology was proposed and fabricated. The PLM amplifier was successfully tested using pulsed signals with various duty cycles to validate the load modulation behaviour of the PLM amplifier and to measure the amplifier's efficiency at different output power back-off levels. In this test, the PLM amplifier exhibited a drain efficiency of higher than 46% in a 9-dB back-off power region, which was significantly better than the balanced class-B amplifier. More evaluations on the performance of the PLM amplifier were carried out using a real LTE signal. In order to digitally control the gate biases of the driver amplifier and two PAs in the PLM amplifier measurement setup, the envelope of the LTE signal was modulated using a delta-sigma modulation scheme, with a field-programmable gate array (FPGA) as the baseband processing source.

The activities carried out within this research direction are supported through an NSERC Collaborative Research grant, AITF funds and industrial cash and in-kind contributions (Ericsson Canada).

Multiband and Multimode SDR-Based Transmitters

This research direction 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 multiband, multi-standard and multi-antenna applications that can be quickly controlled through the ease of software re-configurability. In the context of a reconfigurable baseband transmitter platform, we have proposed multi-standard, multimode SDR-based transmitters that incorporate a dual-band PA, based on the high-efficiency Doherty amplifier, and a channel-selective digital predistortion (DPD) system for linearization purposes. The amplifier design has been fabricated and tested. A new dual-band predistortion methodology has already been established and is being implemented in an FPGA-based DSP (digital signal processing) platform. A similar RF-DPD platform suitable for dual-band application in repeaters has been developed and is under evaluation.

The dual-band Doherty PA has been designed for performance optimization with dual-band offset lines, which are used to transform any non-open circuit conditions at an auxiliary PA to open circuit conditions by providing the necessary phase shift to output reflection coefficient of the auxiliary PA. A stub-loaded dispersive structure has been used to obtain distinct phase shifts at two different frequencies. Further optimization has been done in terms of unequal power division with different frequency bands. In a dual-band Doherty PA architecture, the device and associated circuitries behave differently at different frequencies; therefore, the requirement of an unequal power division ratio in favour of an auxiliary PA can be different at two different frequencies. This requires that the input have an unequal power divider, which has distinct power division ratios at two different frequencies. Such a power divider has been designed using a micro strip stub-loaded structure, and a quasi-analytical methodology has been developed for the design of such circuits. Moreover, efforts towards LTCC (low-temperature co-fired ceramic) design have also been initiated, in order to target high-power multiband applications in multilayer ceramic circuit technology.

Linearization and efficiency enhancement of multiband transmitters: A common trend for increasing wireless transmitter throughput and performance is the concurrent use of multiple transmitter frequencies. The consequence of this type of architecture is the complexity involved for the compensation of transmitter and nonlinearity imperfections. A look-up table (LUT) based predistorter for dual-band systems was implemented to reduce the number of arithmetic operations that exist in the application of the predistorter. In addition, a joint dual-input Volterra model was proposed for the mutual compensation of the intermodulation and cross-modulation effects of the dual-band PA, as well as the in-phase/quadrature (I/Q) impairments in the multiband transmitter, where there is greater emphasis on effects than in the single-band case.

In the feedback path of the PA, any imperfections in the down-converter introduce analytical errors in behavioural model extraction. A new algorithm was used to eliminate these demodulator errors and still give high linearization performance. Over the last year, the first tri-band DPD using WiMAX, WCDMA and LTE signals was introduced for nonlinearity compensation across wide operating frequencies (over 1 GHz). The tri-band DPD was also extended to include third order-intermodulation products and further higher-order products, in order to enhance the performance of the DPD in different spectral bands.

Many PA architectures have been suggested to reduce greenhouse gas emissions and enhance overall efficiency. Among these solutions, the envelope-tracking (ET) technique is a promising solution to improve PA efficiency for high peak-to-average ratio signals. By adapting the power supply voltage dynamically according to the input signal envelope, the PA will always approach saturation and result in high efficiency. A testbed system was developed for a single-band transmitter and produced good performance combined with DPD. Research is currently being conducted on implementation issues and performance improvement for dual-band and tri-band systems.

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

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

Integrated Circuit Design – Microwave and Millimeter Wave

The growing demand for high-performance and low-cost integrated systems requires a great deal of research on integrated circuits, especially for 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.

GaN MMIC PAs: The first thrust of this project is the design of wideband GaN (gallium nitride) MMIC (monolithic microwave integrated circuit) PAs for wireless communication applications. MMICs are of great interest in RF/microwave applications, due to their smaller size compared to that of hybrid circuits. Among the existing microwave device technologies, GaN is particularly suitable for MMIC PA applications, due to its superior performance over other technologies, such as gallium arsenide (GaAs) and silicon, which provides potential for the design of high-power, high-efficiency and broadband PAs. While a particular semiconductor technology may be amenable to implementing high-efficiency broadband PAs, the selection of a suitable PA class of operation and its structure are perhaps even more important for wide bandwidth designs. Switching-mode PAs make transistors act as switches that can be in either in an ON or OFF state. This theoretically suppresses the overlap of the intrinsic drain voltage and current waveforms and increases efficiency. These switching-mode PAs normally exhibit narrowband frequency performance (less than 10%) and make them less appealing for broadband applications. On the other hand, in linear mode amplifiers, such as classes-A, AB and B, the PA works based on presenting the optimal load impedance to the intrinsic drain of the transistor and is less efficient than switching-mode PAs. Nevertheless, harmonically tuned class-B PAs can theoretically achieve peak efficiencies as high as 78.5%. However, the bandwidth of these PAs is also limited due to the difficulty in the realization of their low-impedance harmonic load terminations over a wide bandwidth.

A recently proposed linear class-J mode of operation with proper fundamental and second harmonic impedances appears to be a promising solution for the linearity, efficiency and bandwidth requirements in a single PA design. Originating from linear class-B operation mode, class-J was theoretically shown to achieve the output power, gain and efficiencies as high as those of "deep" class-AB and class-B PAs. In addition, through presentation of the proper impedances to the transistor current source over a specific design space, class-J PAs are expected to achieve broad bandwidth operations.

Combining the advantages of GaN technology and the class-J PA, the design of a broadband single-stage integrated GaN class-J PA is one of the milestones in this integrated PA design project. Two year ago, we started this project with a design of class-J PA chip with an output power of 27 dBm (0.5 Watt) and a drain efficiency of 50%. The design was in 800-nm GaN technology, and the efficiency stayed above 50% in a frequency bandwidth of about 800 MHz from 2.3 GHz to 3.1 GHz.

In PA applications, the transistor works in a highly nonlinear regime, and there is no accurate nonlinear model to simulate the behaviour of the transistor. Therefore, a reliable PA design that achieves the desired output power and efficiency is based on load-pull measurement results to obtain the proper impedances that must be presented to the transistor. With this knowledge, last year, we prepared and arranged a setup to perform the load-pull on-wafer on an integrated stabilized on-chip 500-nm GaN transistor. By providing all the required bias and harmonic impedances, we obtained the proper input impedance as well as the output power and efficiency contours of a class-J PA on the design space, as expected. Based on the measured impedances, we designed and submitted the second version of a fully integrated class-J GaN PA to be fabricated by CMC. This chip is a 1-Watt PA with about an efficiency of 60% working in a broad bandwidth of about 1 GHz centred at 2.5 GHz.

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

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

Millimeter-wave receiver: A six-port based receiver circuit has been developed in LTCC technology for 60 GHz applications. This receiver front-end circuit will be used in conjunction with the digital signal processing (DSP) algorithms developed for single-band and multiband concurrent radio receiver applications using the six-port technique.

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 are also supported through an NSERC discovery grant and AITF funds.

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 2011 to March 2016. The overall long-term objective is the investigation of the scientific and technical problems related to software reconfigurable radio technology suitable for green broadband and ultra-wideband communications and for multi-standard and multimode handsets and base stations. This objective 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 intelligent software-defined radio (SDR) transceivers suitable for concurrent multi-standard and multicarrier applications. As a continuation of past achievements in the modeling and design of switching-mode PAs and radio systems, new design approaches and methodologies will be investigated, in order to achieve better power efficiency for multi-standard and multicarrier signals. New all-digital architectures will be proposed and implemented to ensure the flexibility and ease of the reconfigurability of the entire RF front-end. New topologies involving high-performance, lower power consumption RF DACs (digital-to-analog converters) will be mitigated, in order to offer a solution that minimizes the nonlinearity and power consumption in mixers, while ensuring better configurability for difference frequency bands and standards.

Signal processing techniques, such as signal decomposition, noise shaping, noise reduction, linearization and equalization, will be investigated; and, new approaches and better practices will be proposed to significantly lower the energy consumption of the transmitter, while maintaining good quality of the signal at the antenna.

MIMO Radio Systems

To increase the spectrum efficiency and channel capacity in wireless transmissions, new architectures based on MIMO (multiple input, multiple output) systems will be proposed. These MIMO transceiver architectures will overcome the performance degradation in conventional MIMO systems, which are caused by the combined effect of components' impairments and the cross-coupling between the transmitter and receiver branches. This research thrust aims at the proposal of innovative system architectures and signal processing algorithms that shield MIMO radios from these analog circuit impairments and from problems triggered by the proximity of crosstalk between adjacent branches in MIMO radios. Moreover, since these algorithms have high complexity that increases exponentially with the number of inputs and outputs in MIMO systems, working on proposing low-complexity algorithms and reducing the complexity of existing solutions is important in making the implementation of these solutions possible and allowing us to move toward solutions with higher numbers of inputs and outputs in MIMO systems.

UWB/MM-Wave Radios

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

On the receiver side, a six-port-based receiver for the 60-GHz frequency band using LTCC technology will be investigated and tested. Its performance will be assessed and optimized using low-complexity calibration techniques.

DSP for Wireless Communications

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

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

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. 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. Subsampling techniques will be further investigated, and solutions that reduce the effect of thermal noise folding and interference will be adopted. Initial studies show that using delta-sigma modulation along with subsampling in the receiver allows for pushing of the thermal and quantization noise away from the useful band of the signal and, thus, providing an interesting solution for all-digital receiver design. Application to multiband and multi-standard wireless communications and concurrent multiband receivers will be considered in the coming years. A proof-of-concept prototype for a concurrent multiband subsampling receiver that is able to down-convert signals with carrier frequencies between 500 MHz and 4 GHz will be designed and tested.

A second architecture for adaptive receivers consists of using a passive 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. Calibration algorithms able to compensate for the power detector static nonlinearity allowed a signal-to-noise ratio (SNR) of about 30 dB for the received signals of a bandwidth lower than 5 MHz. Increasing the signal bandwidth results in deterioration of the signal quality (SNR degrades by more than 10 dB for a signal with a 20-MHz bandwidth), due to the frequency response of the receiver and the memory effects of the diodes. Dynamic linearization and calibration algorithms able to compensate for the frequency response and the dynamics have been investigated to enable UWB reception capabilities in the six-port receiver. Concurrent multi-standard reception using the six-port receiver will be the main focus of the coming years. The development of multi-standard calibration algorithms will allow for the reduction of the interference and distortion in the receiver and for good quality signals at the output. Testing with 4G standards, such LTE-Advanced signals, will be carried out to investigate the possibility of using the current frame header as a training sequence or to propose alternatives. 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.

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. Moreover, one graduate student from École Polytechnique de Montréal is currently supervised by Dr. F.M. Ghannouchi.
Université de Québec: Dr. A. Kouki	The ongoing theme of collaboration is related to LINC-based amplifiers and GaN transistors modeling.
International Collaborations	
Participants	**Nature of Collaboration**
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 Multi- band Transmitters design and linearization
Indian Institute of Technologies Dr Mohamad S. Hashemi	The ongoing collaboration is related Waveform Engineering in amplifiers 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. F.M. Ghannouchi is co-supervising the work of three Ph.D. candidates.
Hail University, KSA Dr. N. Boulejfene	The ongoing collaboration is related behavior modeling of wireless transmitters
King Fahd University of Petroleum and Minerals : Dr. Oualid Hammi	The ongoing collaboration is related linearization of wireless transmitters
Ningbo University, China: Prof. T. Liu	Collaboration was initiated this year. Ongoing research activities are related to the modeling and compensation of memory effects in RF power amplifiers.
Tsinghua University, Beijing, China: Prof. Z. H. Feng	Collaboration was initiated this year. Ongoing research activities are related to the design of dual-band Doherty PAs.
Amirkabir University, Iran: Prof. A. Mohammadi	Collaboration was initiated this year. Ongoing research activities on six-port receivers and MIMO wireless systems.

7. GRADUATES

PH.D. Graduates			
Name	Degree	Research Topic	Current Position
Ramzi Darraji	PhD	Digital Doherty amplifiers	PDF at U of Calgary
K. Rawat	PhD	Multi- standards Transmitters	Assistant Professor, ITT, Delhi
M. Rawat	PhD	Neural Network based behavior Modeling	Assistant Professor, ITT, Delhi
M. Mojtaba Ebrahimi	PhD	All-Digital Transmitters	PDF at U of Calgary

M.Sc. Graduates			
Name	Degree	Research Topic	Current Position
Shubhrajit Bhattacharjee	M. Sc.	Impairment Compensation of Wireless Transmitters	Engineer in SNC Lavalin , Calgary
Abul Hasan	M. Sc.	Six-port Receivers	PhD at U of Calgary

8. INTELLECTUAL PROPERTY

Patents and Patent Applications:

1. F. M. Ghannouchi, A. S. Bassam, M. Helaoui and A. Kwan "Digital Multi-band Predistortion Linearizer with Nonlinear Subsampling Algorithm in the Feedback Loop" US patent application, 20130094610, Publication date April 18, 2013.
2. F. M. Ghannouchi, A. S. Bassam, M. Helaoui and A. Kwan "Extended Bandwidth Digital Doherty Transmitters " US patent application, 20100294387, Publication date November 22, 2012

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1. M. Younes and F. M. Ghannouchi, "On the Modeling and Linearization of a Concurrent Dual-Band Transmitter Exhibiting Nonlinear Distortion and Hardware Impairments," IEEE Transactions on Circuits and Systems I, 2013 accepted.
2. F. M. Ghannouchi, M. Younes and M. Rawat, "Distortion and Impairments Mitigation and Compensation of Single and Multi-band Wireless Transmitters," IET Microwaves, Antennas & Propagation, 2013 accepted.
3. B. Georgescu, R. Salmeh, M. Fattouche and F. M. Ghannouchi, "Two-Tone Phase Delay Control of Center Frequency and Bandwidth in Low-Noise-Amplifier RF Front Ends," IEEE Transactions on Circuits and Systems II: Express Briefs, 2013 accepted.
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10. M. Rawat, K. Rawat, M. Younes and F. M. Ghannouchi, "Joint Mitigation of Non-Linearity and modulator imperfections in a dual-band Concurrent Transmitter Using Neural Networks," IET Electronics Letters, Vol. 49: Issue 4, pp. 253-255, February 2013.
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12. D. Wang, M. Fattouche and F. M. Ghannouchi, "Geometry-based Doppler Analysis for GPS receivers," Wireless Personal Communications, Vol. 68: Issue 1, pp. 1-13, January 2013.
13. K. Rawat, M. Rawat, M. S. Hashmi and F. M. Ghannouchi, "Dual-Band Branch-Line Hybrid With Distinct Power Division Ratio Over The Two Bands," Wiley International Journal of RF and Microwave Computer-Aided Engineering, Vol. 23: Issue 1, pp. 90 - 98, January 2013.
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15. M. M. Ebrahimi, M. Helaoui and F. M. Ghannouchi, "Delta-Sigma-Based Transmitters: Advantages and Disadvantages," IEEE Microwave Magazine, Vol. 14: Issue 1, pp. 68-78, January 2013.
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11. J. G. Oya, A. Kwan, S. A. Bassam, F. Munoz and F. M. Ghannouchi, "Optimization of Subsampling Dual Band Receivers Design in Nonlinear Systems," in 2012 IEEE MTT-S International Microwave Symposium Digest (IMS'2012), Montreal, QC, pp. 1-3, 17-22 June 2012.
12. X. Li, W. Chen, Z. Lu, Z. Feng, Y. Chen and F. M. Ghannouchi, "Design of dual-band multi-way Doherty power amplifiers," in 2012 IEEE MTT-S International Microwave Symposium Digest (IMS'2012), Montreal, QC, pp. 1-3, 17-22 June 2012.
13. Hasan, M. Helaoui and F. M. Ghannouchi, "Dynamic Linearization of Diodes for High Speed and Peak Power Detection Applications," in 2012 IEEE MTT-S International Microwave Symposium Digest (IMS'2012), Montreal, QC, pp. 1-3, 17-22 June 2012.
14. Z. Huang, W.-H. Chen, Z.-H. Feng and F. M. Ghannouchi, "Forward Behavioral Modeling of Concurrent Dual-Band Power Amplifiers Using Extended Real Valued Time Delay Neural Networks," in 2012 International Conference of Microwave and Millimeter Wave Technology (ICMMT'2012), Shenzhen, China, pp. 1-4, 5-8 May 2012.
15. K. Rawat and F. M. Ghannouchi, "Load-Pull Assisted CAD design of Inverted Doherty Power Amplifier Without Quarter-Wave Transformer," in 25th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2012), Montreal, QC, pp. 1-4, 29 April - 2 May 2012.

Books and Book Chapters:

1. F. M. Ghannouchi and M. S. Hashmi, Load-Pull Techniques with Applications to Power Amplifier Design. Springer, 2012. [URL]
2. J. R. G. Oya, A. Kwan, F. M. Chavero, F. M. Ghannouchi, M. Helaoui, F. M. Lasso, E. López-Morillo and A. T. Silgado, "Subsampling Receivers with Applications to Software Defined Radio Systems" in Data Acquisition Applications, Intech, 2012.[URL]

Special/Invited Presentations:

1. Professor F. M. Ghannouchi as an Emeritus Distinguish Microwave Lecturer gave an invited talk entitled "Digital Amplifiers for 4G+ Transmitters" Swedish Institute of Technology, Stockholm, on June 9th, 2012

2. Professor F. M. Ghannouchi as an Emeritus Distinguish Microwave Lecturer gave an invited talk entitled "Advanced Transmitters for SDR applications" at University of Tunis, on February 18th, 2013.

3. Professor F. M. Ghannouchi as a invited speaker gave an talk entitled "Power Amplifiers for Green Radio Terminals" at Rochester Institute of Technology, Dubai, UAE on February 14th, 2013.

4. Professor F. M. Ghannouchi as a Keynote Speaker gave a talk entitled “Toward Green Communications” at American University of Sharjah, UAE on February 13th, 2013.

5. Professor F. M. Ghannouchi as a Distinguish Microwave Lecturer gave an invited talk entitled "Advanced Transmitters for SDR applications” at Zhejiang University, Hangzhou November 29th, 2012.
6. Professor F. M. Ghannouchi gave an invited talk entitled "Green Electronics and Wireless Technology" at Ningbo University Ningbo, China, November 28th, 2012.

Seminars:

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

10. OUTREACH

The community outreach activities of iRadio Lab included:

The iRadio group participated in several activities at U of C to promote and recruit students to the Electrical and Computer Engineering program. In May of 2012, the iRadio lab was one of the groups representing the Electrical and Computer Engineering's research section at the Schulich School of Engineering Block Party. The opportunity gave undergraduate students and alumni insight on the research work performed by the iRadio lab and UofC. We have also participated in the annual AITF Summit, held in Banff, Alberta, August 2012.

The iRadio lab held an exhibition booth at the 13th Annual Tech Showcase & Open House presented by Innovate Calgary in October, 2012 to showcase our research to industry partners. In addition to attending exhibitions and conferences, we have attracted industrial partners to hold training seminars for the ECE department and its students.

11. FINANCIAL REPORTS

AITF Revenues/Expenses

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

Funding Sources

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

Funding Sources:

- AITFAlberta 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