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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 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 Technologies 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 first seven-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 and multiple input, multiple output (MIMO) systems. The planned research program for this second mandate 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 five 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, 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 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).

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 29 refereed journal papers (published and accepted), 20 refereed conference papers (published and accepted), 2 patent applications and 2 US patents allowed and the publication of one book chapter. 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 a Killam scholarship; and, a second Ph.D. student, Mayada Younes, was the recipient of an AITF-ICT Award. Xiang Li was the recipient of AITF Doctoral Award for Chinese Students.

During its eight year, iRadio Lab was successful in securing substantial funding: $160 K from the Natural Sciences and Engineering Research Council of Canada (NSERC). These monies supplement the $850 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 $150 K from industry partners 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 $116 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, two associated faculty members, one technical support staff, one administrative support staff, two lab managers, seven postdoctoral fellows and twenty-three 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 Chair's renewal proposal.

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 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.

Millimeter (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.

Energy efficient (green) wireless networks: To address the ever-increasing demand for higher data rates and better quality of service, the wireless network standards have mainly focused on increasing the amount of bits per second that can be reliably transmitted per one Hertz of frequency spectrum, a performance measure known as spectral efficiency (SE). However, this increase in the SE achieved through the advent of new modulation techniques, such as orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA), comes at the price of a reduction in the so-called energy efficiency (EE), i.e. the number of reliably transmitted information bits per one joule of consumed energy. Quantifying this inherent trade-off between SE and EE in the current wireless network standards and improving it by inventing new modulation and power allocation techniques are necessary and important steps toward the design of energy efficient and eco-friendly wireless networks of the future.

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 PA (power amplifier) is a crucial part of any wireless transmitter. Regardless of the type of transmitter that the PA is used in (a base station or a mobile terminal), its power loss dominates that of other transmitters' blocks. Therefore, improving the PA power efficiency considerably increases the whole transmitter power efficiency. To achieve this goal, switching-mode power amplifiers (SMPAs) are proposed to minimize the dissipated power in the transistor, thereby maximizing their power efficiency. Extensive research has been performed during the last few years to improve the performance of such inherently narrow band SMPAs.

In SDR (software-defined radio) system applications, a broadband SMPA that can operate with different signal standards at different carrier frequencies is highly desired. A single broadband highly efficient PA would optimize the efficiency, complexity and implementation cost of such transmitters. Compared with class-F and class-D SMPAs, class-E PAs are easier to design for broadband applications (due to their relative simplicity) and more effective in the realization of the output load impedance networks (due to their required high-impedance load conditions for the harmonic frequencies). Therefore, a methodology to design broadband class-E PAs using a packaged gallium nitride (GaN) high-electron-mobility transistor (HEMT) at RF frequency is proposed. This approach is based on the analysis of load-pull / source-pull measurement data to determine the optimal load and source reflection coefficients that maximize power-added efficiency (PAE) and power gain within the design bandwidth, respectively. The input and output matching networks of this method are based on a low-pass, multistage impedance transformer and a simplified real frequency technique.

Based on load-/source-pull measurement data, this design approach has been applied to a Cree CGH40025 (a 25 W packaged GaN HEMT); and, two different lumped element broadband configurations were selected to design input and output matching circuits. A fourth-order low-pass impedance transformation topology was designed as the output matching network to provide the optimal load reflection coefficients in the targeted bandwidth (1.8 to 2.7 GHz). On the other hand, a band-pass configuration was chosen to synthesize the optimal source reflection coefficients, as they are spread in a wider area in the Smith chart. Under a continuous wave (CW) test condition, the fabricated PA showed a PAE of more than 48% and output of power of 16-29 W in the frequency band of 1.8 - 2.7 GHz for a fixed DC bias condition. The designed broadband PA is suitable for delta-sigma modulation based transmitters in the long term evolution (LTE) signal standard frequency range. The PA has demonstrated a PAE of more than 48% all over the frequency band when driven with a delta-sigma modulated LTE downlink signal, while the quality of the signal was comparable to that of the original input signal. The PA was tested with global system for mobile communications (GSM) signals at 1.96 GHz, and an output power of 43.8 dBm with a drain efficiency of 60% was achieved.

Continuous-mode PAs: In the continuation of the research on continuous-mode PAs, a thorough investigation of the behaviour of the transistor under sub-pinchoff gate voltages was performed. This analysis has led to a new class of PAs, designated as continuous class-C PAs, where the design space for the load impedance is independent of the input power and bias gate voltage, leading to two categories of operation modes, namely high-power and low-power continuous class-C. These concepts were practically validated through the implementation of an integrated CMOS (complementary metal-oxide semiconductor) amplifier, of which the design space was found using an on-wafer load-pull system. It has also been verified that this integrated continuous class-C PA is able to maintain a constant output power and PAE at different frequencies over a specific bandwidth.

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), Canadian Microsystem Corporation (CMC) and Université de Québec in Montréal.

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

Digital Doherty PAs: In continuation of work done in the previous year on the design of broad bandwidth, digitally driven Doherty PAs, a new architecture of frequency-agile Doherty PA based RF front-end was implemented. This 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 proposed equalizer are synthesized to compensate for the non-ideal frequency behaviour of the RF building blocks of the Doherty PA.

It has been shown that the proposed architecture enables the Doherty PA to operate with significantly improved power efficiency and linearity performance beyond its nominal frequency of design, which is suitable for multi-standard applications. As a matter of fact, when driven with a 140-MHz bandwidth LTE signal centred around 2.30 GHz, the average efficiency of a 2.14-GHz Doherty PA prototype with the proposed digital baseband equalizer 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 addition, when operated in concurrent dual-band mode with two 20-MHz bandwidth LTE signals centered at 1.96 and 2.34 GHz, the proposed Doherty PA enabled a reduction in DC power consumption by nearly 15%. It was demonstrated that the integration of the proposed baseband equalizer does not compromise the linearizability of the Doherty PA.

Integrated load-modulated PAs: For the transformer-less load-modulated (TLLM) amplifier proposed in previous years, a compact and flexible amplifier architecture was proposed for high-efficiency PAs with arbitrary source/load impedances. Using this amplifier, there is no need for additional matching networks between the PA and the transmitting antenna. Moreover, at the input, the divider, matching networks and phase alignment components are all integrated in a very compact input network that minimizes the circuit footprint and losses associated with the additional components. These features are of more importance in integrated designs where minimization of the chip area reduces production cost and minimization of losses improves the overall system performance and efficiency. This amplifier has been validated in simulation, and discrete prototypes of this amplifier are being fabricated to validate its benefits and performance.

Advanced Adaptive DSP Algorithms for Wireless Transceivers

Multiple input, multiple output (MIMO) systems enhance the data transmission rate and/or signal integrity by utilizing several frequency channels. Adding multiple broadcast transmitters introduces more complexity into the design and requires innovative solutions to regulate efficiency or compensate for impairments. Inline DSP (digital signal processing) algorithms are used to handle such scenarios in MIMO systems.

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

MIMO transmitters are typically integrated on a single chip. Due to the limitations in the isolation between the transmitter ports of the PAs in the chip, crosstalk occurs in linear and nonlinear forms. The coupling at the inputs of the PAs has been considered as nonlinear crosstalk after its passage through the PAs. A novel technique to streamline the 2x2 digital predistortion (DPD) by estimation of two 1x1 DPDs has been proposed, which may successfully linearize the nonlinear MIMO system, but with approximately half of the complexity of the conventional technique.

The DPD technique has been widely used to linearize transmitters. The problem with DPD is that the peak-to-average power ratio (PAPR) increases after applying the expanding gain. The gain expansion, in turn, increases the amount of back-off and limits improvements in efficiency. A novel idea has been investigated to obtain the maximum possible efficiency while meeting the linearity requirements. In this approach, the PA is driven by the signal such that it passes the spectral mask requirements. The distortions of the PA are then compensated at the receiver by estimating the statistical distribution of the power in the received signal. Knowing the distribution of the transmitted signal, one can estimate the nonlinearity and compensate for it. A phase-only DPD can be applied at the transmitter to compensate for the phase distortions. This does not impact or change the PAPR of the transmitted signal; hence, the transmitter efficiency remains unaffected.

Many crest factor reduction (CFR) techniques have been proposed in the literature to reduce the high PAPR of modern communication signals. In this research, a new CFR technique has been explored with the objective of minimizing the PAPR of the signal while meeting the adjacent channel power ratio (ACPR) and linearity requirements. The proposed technique combines DPD for PA linearization at the transmitter, and the CFR function is compensated for at the receiver. Therefore, this technique provides the best performance in terms of efficiency and error vector magnitude (EVM), while meeting the ACPR requirements.

Transmitter hardware impairments: Transmitter digital domain linearization solutions of the different RF imperfections are constantly evolving to extract optimal benefits in terms of cost, performance and flexibility. The PA is the most inherent nonlinear device in any conventional transmitter and the main source of distortion. The other major RF impairments in the wireless transmitter originate from the antenna, non-constant group delay variations in band-pass filters, and the modulators required for up-conversion of the transmitted signals. These imperfections include relative amplitude and phase mismatches between the in-phase and quadrature-phase (I and Q) signal branches of quadrature modulator direct-conversion radios, which result in self-interference or adjacent channel interference depending on the spectral content of the baseband I and Q signals.

A rational function based model capable of alleviating the effects of PA nonlinearity and I/Q imbalance was also proposed. This model compensates for these imperfections in a joint manner. In addition, a distributed memory polynomial based two-block model was proposed, which also aims to mitigate these imperfections.

Adaptive and Tuneable Receivers

Wideband and multiband radio receivers are highly desirable for the flexibility that they provide 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 the 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 was replaced with broadband passive components. These six-port receivers were tested under fading environments and dual-band conditions.

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

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 band-pass 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 circuits, an ADC component and a band-pass filter bank, twelve different dual-band signals have been received with better SNR performance.

The utilization of dual-band PAs and DPD (digital predistortion) typically requires two transmitters for the bands and two receivers in the feedback loop. A study has 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: A new signal processing algorithm for the six-port based direct down-conversion receiver has been proposed that reduces the signal processing complexity. This algorithm was tested in an ultra-wideband (UWB, 2-18 GHz) receiver prototype and benchmarked against previous work. It was found to achieve similar performance, but with much less computational complexity.

A comprehensive study has been carried out to identify the advantages and drawbacks of the existing six-port based direct down-conversion receiver in comparison to a commercially available communication receiver system, in terms of input RF bandwidth, demodulation bandwidth, circuit complexity, port matching and isolations, power requirement, received signal quality, noise performance, sensitivity, dynamic range, intermodulation performance, cost, and overall conversion gain. In some aspects, the six-port based direct down-conversion receiver has advantages over any commercially available receiver, while it lacks performance in other domains. The areas where the receiver was found to be lacking performance have been identified; and, research is in progress to improve the capability of its architecture in these identified areas.

The use of the six-port receiver in real communication systems was investigated. A WCDMA (wideband code division multiple access) downlink communication path in a multipath fading channel environment was simulated with varying signal-to-noise ratios. The prototype of the UWB six-port receiver (2-18 GHz) was used as the front-end receiver in the communication system. Results of the bit error rate demonstrated a very good performance, very close to assuming a perfect receiver front-end in the communication system.

Concurrent dual-band six-port receivers: Concurrent dual-band receivers are gaining a lot of interest, because they enable a mobile terminal's users to access to two wireless services simultaneously and also 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 size, cost and the power requirement of the receiver. The six-port receiver option was explored as an alternative, where 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.

A new signal processing algorithm was also developed for nonlinear calibration of the concurrent dual-band receiver. The developed receiver and calibration technique improved performance significantly and enabled its use to receive real communication signals. In order to verify that the developed receiver can operate in multi-standard and multiband

scenarios, WCDMA 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.

SDR Transmitters

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 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 multilevel 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.

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).

Multilevel delta-sigma based transmitters: Multilevel delta-sigma modulators (DSMs) are a promising solution for the enhancement of power efficiency of SDR transmitters and have been investigated during the last year. A level de-multiplexed, multilevel DSM transmitter architecture was designed, implemented and measured. The design was based on two SMPAs connected together by a T-junction transmission line, which acts as a combiner. In order to improve the efficiency and the bandwidth of the architecture, two wideband amplifiers have been designed and implemented in back-to-back direct connections. The amplification block has been tested, and measurement results have shown its potential in achieving high efficiency and wideband applicability.

Performance enhancement in delta-sigma based transmitters: Efficiency and bandwidth limitations affect the performance of delta-sigma based transmitters and compromise their use in SDR applications. In fact, the efficiency and bandwidth performance of SDR-based transmitters is constrained by the presence of quantization noise from DSMs. An adaptive noise suppression (ANS) technique has been developed in multilevel complex DSMs to improve the performance of the transmitter. This technique targets to ease the specification of the final stage RF band-pass filter for the signal prior to transmission. The ANS technique was applied on multilevel complex DSM output signals, and the measurement results show a potential to design wideband and high-efficiency DSM-based transmitters.

Pulsed load modulation transmitters aim to provide a complete digital transmitter using high-efficiency pulsed load modulation (PLM) PAs for base station applications. The concept of using a PLM PA for design of the proposed transmitter prototype is the encoding of the envelope information of the standard signal at the baseband part using programming devices (such as field programmable gate arrays) and the modulation of the gate bias supply of the transistors, instead of the drain bias supply. The main advantage of using an envelope encoder is that the PA operates with a constant envelope input, which results in achieving high efficiency compared to signals with high peak-to-average power ratios (PAPRs).

Digital load modulation in the PLM technique keeps the average efficiency of the PA at its maximum value for up to 6 dB of output power back-off (OPBO) from the maximum peak power, offering better performance in terms of power efficiency at the OPBO region than the well-known Doherty PA. In addition to maintain high efficiency, the linearity of the system is less subjective to the nonlinearity of the device. On the other hand, by encoding the gates of the transistors in the proposed PLM based transmitter rather than the drain supply, there is no need to use high speed switching power regulators.

The complete digital transmitter prototype was developed by implementing a high-power PLM PA. To provide constant envelope data, a delta-sigma modulator was used to transform the envelope signal into a binary digital signal. The PA was designed and implemented using 10W GaN HEMT devices at a carrier frequency of 2.35 GHz. The average drain efficiency of the PA, tested by a continuous wave signal, reached 60.5% at the maximum output power of 43 dBm.

Different signal standards with different PAPRs were used to validate the performance of the transmitter prototype and the linearity of the designed PA. For an LTE signal with a 6 dB PAPR and 1.4 MHz bandwidth, the PLM PA exhibited a drain efficiency of 54.0% and power-added-efficiency (PAE) of 50.4%. For a 5 MHz bandwidth LTE downlink signal with 11 dB PAPR, the PA delivered an average output power of 33.5 dBm. The adjacent channel leakage ratio (ACLR) was found to be -38.78 dBc and -36.85 dBc at the lower 10 MHz offset frequency and the upper 10 MHz offset frequency, respectively.

All-digital mixer-less polar transmitter: In this project, a new polar RFDAC (RF digital-to-analog converter) transmitter architecture that uses an analog RF variable gain amplifier and an analog phase shifter was proposed. This architecture translates the baseband phase signal to RF domain without using mixers and quadrature up-converters. Accordingly, spurs and distortions that are typically associated with the mixers are negated over a wide frequency band, and no filtering is needed to meet the spectrum emission mask. The absence of a RF band-pass filter eliminates the operating frequency constraint and makes the transmitter reconfigurable. The performance of the transmitter was successfully tested using LTE signals, and the signal quality was assessed in terms of error vector magnitude.

Multiband and Multimode SDR-Based Transmitters

Multiband transmitters are suitable candidates and very promising architectures for modern wireless communication systems, such as carrier aggregated LTE Advanced systems. Carrier aggregated LTE is an efficient way to increase the signal bandwidth within the available spectrum. Therefore, multiband transmitter architectures should operate in both single and concurrent modes, in order to support the intra-band and inter-band aggregated carriers in LTE Advanced systems.

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

Linearization of multiband transmitters: Due to the increasing demands for large-capacity and high-performance wireless transmitters, multiband, multi-standard transmitter architectures play an important role in modern communication. However, the consequence of this type of architecture over traditional single-band transmitters is the elevated signal processing complexity involved for the compensation of transmitter and nonlinearity imperfections.

The analysis of dual-band DPD (digital predistortion) techniques has been extended in order to include the effects of the phase distortion in tri-band transmitters. Since manufacturing processes cannot replicate any component perfectly, there are deviations between manufactured RF filters; and, the phase response in each RF filter differs. Moreover, using wider bandwidth signals causes differences in the group delay between each band. Thus, the transmitter phase distortion affects the transmission quality and needs to be compensated for. A novel 3-D phase-aligned DPD is proposed that takes into account both the compound amplitude and phase variation effects in a concurrent tri-band transmitter.

On the other hand, in order to reduce the computational complexity of multiband DPDs, a new multi-branch DPD is proposed for the linearization of dual-band transmitters. The proposed model is based on a distributed polynomial basis function with a radial pruning approach. This approach specifically selects the coefficients that are most important for nonlinear compensation in dual-band transmitters.

Envelope tracking for multiband transmitters: RF PAs utilize constant DC supply voltages for operation. For high PAPR (peak-to-average power ratio) signals that are being utilized for maximum spectral efficiency, the efficiency of the amplifier is severely impacted. Through the use of a DC modulator, the amplifier can be adapted such that the supply voltage is a function of the intended output power. This technique, known as envelope tracking (ET), is increasingly attractive for modern radio transmitters. Expanding the application to multiband transmitters requires complex adaptation algorithms to increase both efficiency and linearity of the output signal. A test-bed was developed

to analyze the application of concurrent dual-band ET transmitters, and the efficiency and linearity enhancement on the PA is under investigation. For experimental validation, a 4-carrier WCDMA signal and a 20 MHz wide LTE signal were concurrently sent in separate bands into the ET PA. Using dual-band DPD techniques, the system was able to meet both standards' transmitter specifications.

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.

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.

GaN PAs: Continuous-mode PAs have recently attracted a great deal of attention, due to their suitability for broadband single-stage PA design. The intrinsic drain voltage of the transistor can be manipulated in order to create sets 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 the above concept, a continuous-mode integrated GaN (gallium nitride) PA design project has been carried out over the last few years. The world's first integrated continuous-mode PA operating in class-J mode was designed and fabricated in collaboration with Canada Microelectronic Corporation (CMC). As anticipated by the theory and computer-aided design (CAD) simulations, the measured broadband output power (1 Watt) and power efficiency (70%) performance covered a 1 GHz frequency bandwidth centred around 2.5 GHz.

The second version of the design was created in the last year. In this version, practical modeling problems were tackled, in order to improve the overall power efficiency of the design. Two different types of matching networks – fully integrated and hybrid topologies – have been used and compared. The hybrid topologies were able to minimize the losses and increase the resonance frequency in the inductors, which resulted in a higher overall efficiency of the PA and wider frequency coverage. In addition, different classes of continuous-mode PAs, such as continuous class-C and continuous class-F are being investigated.

CMOS mm-wave PAs: We have proposed a new architecture and design methodology for the 60 GHz Doherty PA with a simpler, low-loss combining network. This amplifier was fabricated and tested using 65-nm CMOS technology. Typical efficiency values published in the literature in the same frequency range in CMOS technology are between 2% and 5%. Our test results have shown an efficiency of more than 8% in the 6 dB OPBO (output power back-off) range.

Millimeter-wave receiver: Another research thrust in the 60 GHz communication band is the development of high-speed, low-cost and low-power millimeter-wave receiver circuits and systems. With rapid growth of high-speed wireless technologies and increasing demand for ultra-high-speed wireless connectivity, the global wireless spectrum regulators have provided new unlicensed spectrum usage in the millimeter range (57-64 GHz) with fewer restrictions on radio parameters. R&Ds in mm-wave circuits and systems have spiked, with rapid progress in the standardization of wireless communications (IEEE802.15.3 and IEEE 802.11ad) in the 60 GHz band. The unlicensed band from 57 GHz to 64 GHz, simply called the 60 GHz band, serves as the focus of current mm-wave research works.

The six-port based quadrature down-conversion has been demonstrated to provide an innovative approach to the design of high-speed, low-cost and low-power wireless systems. It is known that mm-wave technology enables the design of compact and low-cost wireless transceiver systems that can conveniently permit data rates up to several Gb/s. A six-port based receiver circuit has been developed in low-temperature co-fired ceramic (LTCC) technology for the 60 GHz applications. The fabricated six-port receiver circuit has been obtained, and all the components have been flip-chip assembled on the fabricated circuit. The fabricated and assembled circuit is under test for its performance evaluation. 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.

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 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 green software-defined radio (SDR) transmitters suitable for the next generations of wireless communication systems, including the 5^{th} generation (5G) of wireless communication networks. Given the expectations that 5G systems will require substantial increase in bandwidth, the continuation of past achievements in the modeling and design of switching-mode PAs (SMPAs) and radio systems will be focused on proposing new design approaches and methodologies that able to achieve better or at least similar power efficiency over a large frequency band. Continuous-mode SMPAs, such continuous-mode class-F, continuous-mode class-F^{-1} and continuous-mode class-D, will be one of the main focuses of research in this area.

New broadband all-digital architectures that take advantage of the 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 be mitigated, in order to offer a solution that is easily reconfigurable for wide frequency ranges, provides better linearity than state-of-the-art mixer-based solutions, reduces the power consumption compared to switching modulators based mixers, ensures higher dynamic range and higher linearity to meet the requirements of the 5G wireless communication standards. Avoiding the use of filters along the up-conversion path will offer an overall transmitter solution that is easily integrable with a small footprint and at a low cost. These are major features for the next generations of wireless communications, which 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.

MIMO Radio Systems

To increase the spectrum efficiency and channel capacity in wireless transmissions, MIMO (multiple input, multiple output) radio systems have been used over the last few years. The new generations of 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, where 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 implementations.

On the signal processing side, the recently proposed 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 proposing innovative low-complexity algorithms and reducing the complexity of existing solutions is important in making the implementation of these solutions possible for massive MIMO systems of the next generations of wireless communications standards.

UWB/mm-Wave Radios

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) in order to cope with the increase of the traffic load in wireless communication networks of the next generations. Indeed, not only is the data rate per user expected to increase significantly, even the number of users is projected to increase severalfold, which will result in data traffic in the next generations' networks that is hundreds of times higher than the data traffic in the current generation. 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 will be aimed at reducing the effect of the pronounced impairments at this frequency range. Special attention will be given to the amplification topology, where a new transformer-less load-modulated PA 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 new topology of a mixer-less receiver using a six-port wave correlator will be proposed for the 60 GHz frequency band using LTCC technology. The proposed topology will be aimed at improving the receiver dynamic range by taking advantage of the passive feature of the wave correlator to design more selective input ports that reject most of the out-of-band and in-band interference. Low-complexity calibration techniques will also be investigated for implementation in multi-gigahertz bandwidths.

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 observed so far is largely due to the wide bandwidth of the observation path. Accordingly, particular interest will be given 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, which have been proposed for signals with narrower frequency bands, will not be efficient or practical for use with signals having a bandwidth of over 100 MHz. Indeed, such signals result in much higher and more complex nonlinear distortions and memory effects. Using more complex models with high nonlinear and memory orders is 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 high speeds required for such wideband applications. New model complexity reduction techniques, including pruning and compressive sensing, will be proposed to increase the order of nonlinearity and memory without increasing the overall complexity of the model. Low-complexity model identification techniques will also investigated and proposed.

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 and the next generations of wireless communication standards. For the sake of high data rates, these standards consider

the possibility of having simultaneous signal transmissions in multiple frequency bands by aggregating different carriers, in order to achieve more efficient frequency use of the spectrum. When it comes to the realization of CA techniques, the linearization of transmitter architectures supporting CA is of great importance. 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 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.

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 that is able to effectively remove strong interferers. 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. Combining subsampling techniques along with a noise shaping technique, such as delta-sigma modulation, is being investigated, and initial results prove that such topology has the potential to simultaneously address the interference and noise problems in multi-standard receivers. This topology will be further investigated, and practical solutions for implementation that reduce the effect of thermal noise folding and interference will be adopted. 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 in the presence of strong interferers 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. 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 interferers 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.

Energy Efficient Modulation and Resource Allocation for Wireless Networks

The orthogonal frequency division modulation (OFDM) and its multiple-access multi-user variant (OFDMA) are widely used in many different wireless communication standards, such as WiFi (wireless Internet), DVB (digital video broadcasting), WiMAX (worldwide interoperability for microwave access), LTE and LTE Advanced. The reason for their wide application lies in their high efficiency in utilizing the frequency spectrum, their simple digital implementation, and their effectiveness in handling multipath channels. The OFDM technique in conjunction with channel coding is an

optimal strategy for transmission over band-limited AWGN channels when there is a constraint on the overall transmit power. In other words, given a certain amount of available power, an ideal transmitter equipped with a 100 percent efficient power amplifier (PA) can, in theory, use a combination of OFDM and channel coding to achieve the well-known Shannon capacity of a band-limited AWGN (additive white Gaussian noise) channel. In practice, however, the power consumed by the PA is dramatically different from the transmitted power, as a result of the PA's inefficiency. From the point of view of green communications, the power constraint is naturally imposed on the consumed power rather than the transmitted power. Therefore, OFDM is not an optimal modulation technique for use in a practical transmitter; in fact, it performs very poorly, due to its large peak-to-average power ratio (PAPR). Moreover, the channel capacity does not follow the well-known logarithmic expression when a realistic PA is used in the transmitter.

The first goal of this research path is determination of the optimal modulation scheme (i.e. the input distribution) that maximizes the mutual information of a band-limited AWGN channel when a non-ideal transmitter is used and when the total consumed power (rather than the transmit power) is constrained. Moreover, the capacity (i.e. the maximum mutual information) of this channel will be investigated both analytically and using computer simulation. The above tasks will be done for various classes of PAs currently used in wireless transmitters as well as the more advanced PA structures currently being developed for future networks. The optimal modulation scheme will provide the best achievable spectral efficiency (bits/sec/Hertz) versus energy efficiency (bits/Joule) trade-off.

In the next phase, the above work will be extended to a multi-user scenario where a base transceiver station (BTS) equipped with a non-ideal PA simultaneously transmits to multiple users in a band-limited AWGN broadcast channel. Again, the constraint is on the overall power consumed by the BTS transmitter. The goal is determination of the optimal modulation scheme and the optimal power allocated to each user, in order to maximize the total data rate of the users. For similar reasons, OFDMA is not optimal in this scenario when a non-ideal transmitter is used.

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 IEEE-MTT-S' Distinguished Microwave Lecturer Emeritus for period of 2012-2013. 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. M. Fattouche	Professor Research interests include wireless location and communication systems	Dr. Fattouche is associated with iRadio Lab
Dr. L. Belostotski	Assistant professor	Dr. Belostotski is associated with iRadio

	Research interests include CMOS RFIC transceivers design	Lab

VISITING PROFESSOR / RESEARCHERS		
Name	**Role / Topic**	**Awards / Special Info**
Anis Ben Arfi	Internship Student	
Shengjie Bi	Visiting Undergraduate Student	
Deepak Nair	Visiting Ph.D. Student	
Youssef Nouir	Internship Student	
Silong Zhang	Visiting M.Sc. Student	

VISITING SPEAKERS		
Name	**Topic**	**Special Info**
Dr. Oualid Hammi Assistant Professor King Fahd University of Petroleum & Minerals	Mitigation of Power Amplifiers' Distortions Using Compressed Sensing Techniques	
Dr. Taijun Liu Professor Ningbo University	Web-based Remote Nonlinearity Measurement, Nonlinear Distortions and Behavioral Modeling for Power Amplifiers	
Dr. Jeffrey Pawlan Pawlan Communications	An Introduction to Software=Defined Radio for Microwave Engineers	

RESEARCH ASSOCIATES / ASSISTANTS		
Name	**Role / Topic**	**Awards / Special Info**
Abdullah Olopade	Research Associate	
Sharif Rahman	Research Associate	
Dushyant Sharma	Research Associate	

POSTDOCTORAL FELLOWS		
Name	**Role / Topic**	**Awards / Special Info**
Dr. Pouya Aflaki	Switching Mode PA Design for Delta-Sigma Transmitters	Graduated from University of Calgary
Dr. Ramzi Darraji	Wideband Doherty Power Amplifier Design	Best Conference Paper Award (WAMICON'2013), graduated from University of Calgary
Dr. Mohammad Mojtaba Ebrahimi	All Digital Transmitters	Graduated from University of Calgary
Dr. Hongyi Li	Undersampling Bandpass Sigma-Delta Modulator	Graduated from Peking University
Dr. Payam Dehghani Rahimzadeh	Energy Efficient Wireless Networks	Eyes High Postdoctoral Fellowship, graduated from University of Alberta
Dr. Mehdi Vejdani Amiri	MIMO Transmitters	Graduated from University of Calgary

PHD CANDIDATES		
Name	**Role / Topic**	**Awards / Special Info**
Mohammadhassan Akbarpour	Broadband Power Amplifier Design	ICT – Alberta Innovates Award, 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	Supervised by Dr. Mohamed Helaoui
Abubaker Hassan	Wideband Power Amplifier Characterization and Linearization	Supervised by Dr. Fadhel Ghannouchi
Maryam Jouzdani	Digital Transmitters using Pulse Load Modulation	Supervised by Dr. Fadhel Ghannouchi
Andrew Kwan	Multi-band Envelope Tracking Transmitters	Queen Elizabeth II Graduate Scholarship, Annual Progress Report Excellence Award, supervised by Dr. Fadhel Ghannouchi
Xiang Li	Multi-Band Power Amplifier Design	Alberta Doctoral Awards for Chinese Students – Alberta Innovates Award, 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	Izaak Walton Killam Pre-Doctoral Scholarship, supervised by Dr. Fadhel Ghannouchi and Dr. Leo Belostotski
Dimple Sharma	DVB Transceiver Design	Supervised by Dr. Fadhel Ghannouchi
Mayada Younes	Linearization of Multi-band Transmitters	Alberta Innovates Technology Futures (AITF) Doctoral Award, Annual Progress Report Excellence Award, supervised by Dr. Fadhel Ghannouchi

MSC CANDIDATES		
Name	**Role / Topic**	**Awards / Special Info**
Anis Ben Afri	MIMO Impairment Compensation	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
Tushar Sharma	Digital Doherty Transmitters	Supervised by Dr. Fadhel Ghannouchi
Hosein Taghavi	CMOS PA Design	Supervised by Dr. Fadhel Ghannouchi
Milad Tajvidi	MIMO Antenna Beamforming	Annual Progress Report Excellence Award, 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

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

Chris Simon	Technical support
Ivana D'Adamo	Administrative support to Dr. Ghannouchi and the iRadio Lab team

6. COLLABORATIONS

National Collaborations	
Participants	**Nature of Collaboration**
École Polytechnique de Montréal: Dr. K. Wu Dr. 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 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 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 relates 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**
Mehdi Vejdanim Amiri	Ph.D.	Signal Processing Techniques for	PDF at University of Calgary

		Power Efficiency and Signal Quality Enhancement of SISO and MIMO Radio Systems	

M.Sc. Graduates			
Name	**Degree**	**Research Topic**	**Current Position**
Mohsin Aziz	M.Sc.	Rational Function based model for the joint mitigation of I/Q imbalance and PA Nonlinearity	Ph.D. Student at University of Calgary
Abdullah Olopade	M.Sc.	Concurrent Dual-band Six Port Receiver	Researcher at University of Calgary
Sharif Rahman	M.Sc.	Delta-Sigma Modulator for Wideband and Multi-Band Radio Systems	Researcher at University of Calgary

8. INTELLECTUAL PROPERTY

Patents and Patent Applications

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3. F. M. Ghannouchi and R. Darraji, "Extended Bandwidth Digital Doherty Transmitters," PCT patent application, filed July 31, 2013.

9. PUBLICATIONS

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2. D. Wang, F. M. Ghannouchi, Y. Ding and A. Kwan, "70% Energy Saving In Wireless Positioning Systems: Non-Data-Bearing OFDM Transmission Replaces Non-Pulse-Shaping PN Transmission," IEEE Systems Journal, 2013, accepted.
3. 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, 2013, accepted.
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7. A. Harguem, N. Boulejfen, F. M. Ghannouchi and A. Gharsallah, "Robust behavioral modeling of dynamic nonlinearities using Gegenbauer polynomials with application to RF power amplifiers," Wiley International Journal of RF and Microwave Computer-Aided Engineering, Vol. 24: Issue 2, pp. 268-279, March 2014.
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9. A. Hasan and M. Helaoui, "Performance Driven Six-Port Receiver and Its Advantages over Low-IF Receiver Architecture," Journal of Electrical and Computer Engineering, Vol. 2014: Issue 198120, pp. 1-8, February 2014.
10. A. O. Olopade and M. Helaoui, "Performance Analysis of a Six-Port Receiver in a WCDMA Communication System including a Multipath Fading Channel," Journal of Electrical and Computer Engineering, Vol. 2014: Issue 198261, pp. 1-7, January 2014.
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12. A. O. Olopade, A. Hasan and M. Helaoui, "Concurrent Dual-Band Six-Port Receiver for Multi-Standard and Software Defined Radio Applications," IEEE Transactions on Microwave Theory and Techniques, Vol. 61: Issue 12, pp. 4252-4261, December 2013.
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14. F. Elsayed and M. Helaoui, "Linearized Multi-Level DeltaSigma Modulated Wireless Transmitters for SDR Applications Using Simple DLGA Algorithm," IEEE Journal on Emerging and Selected Topics in Circuits and Systems, Vol. 3: Issue 4, pp. 594-601, December 2013.
15. M. M. Ebrahimi and M. Helaoui, "Reducing Quantization Noise to Boost Efficiency and Signal Bandwidth in Delta–Sigma-Based Transmitters," IEEE Transactions on Microwave Theory and Techniques, Vol. 61: Issue 12, pp. 4245-4251, December 2013.
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17. A. H. Abdelhafiz, O. Hammi, A. Zerguine, A. T. Al-Awami and F. M. Ghannouchi, "A PSO Based Memory Polynomial Predistorter With Embedded Dimension Estimation," IEEE Transactions on Broadcasting, Vol. 59: Issue 4, pp. 665-673, December 2013.
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19. M. V. Amiri, S. A. Bassam, M. Helaoui and F. M. Ghannouchi, "Estimation of Crossover DPD Using Orthogonal Polynomials in Fixed Point Arithmetic," AEU International Journal of Electronics and Communications, Vol. 67: Issue 11, pp. 905 - 909, November 2013.

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2. 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 accepted.
3. 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," in 2014 IEEE MTT-S International Microwave Symposium (IMS'2014), Tampa Bay, FL, USA, 1-6 June 2014 accepted.

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7. F. Elsayed, M. Ebrahimi, M. Helaoui and F. M. Ghannouchi, "First- and Second-Order Envelope DSM Circuits," in 2014 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2014), Toronto, ON, 4-7 May 2014 accepted.
8. M. A. Messaoud and F. M. Ghannouchi, "SDR based Multi-band Subsampling Receivers for GNSS Applications," in 2014 International Conference on Advanced Technologies for Signal and Image Processing (ATSIP'2014), Sousse, TN, 17-19 March 2014.
9. A. Zerguine, O. Hammi, A. Abdelhafiz, M. Helaoui and F. M. Ghannouchi, "Behavioral Modeling and Predistortion of Nonlinear Power Amplifiers Based on Adaptive Filtering Techniques," in 11th International Multi-Conference on Systems, Signals and Devices (SSD'2014), Castelldefels-Barcelona, Spain, 11-14 February 2014.
10. M. V. Amiri, M. Helaoui and F. M. Ghannouchi, "Streamlined MIMO Cross-Over Digital Predistortion," in 2014 IEEE Radio and Wireless Symposium (RWS'2014), Newport Beach, CA, USA, 19-22 January 2014.
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12. A. Hasan and M. Helaoui, "Comparative analysis of linear six-port receiver calibration techniques," in 2013 European Microwave Conference (EuMC'2013), Nuremberg, DE, pp. 64-67, 6-10 October 2013.
13. S. Rezaei, L. Belostotski and F. M. Ghannouchi, "1.6 GHz -3 GHz, 10W, 60% Efficiency Class-J PA for Cognitive Radio Applications " in IEEE International Midwest Symposium on Circuits and Systems (MWSCAS'2013), Columbus, OH, USA, pp. 880-883, 4-7 August 2013.
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15. S. Zhang, W. Chen, F. M. Ghannouchi and Z. Feng, "An Iterative Pruning of 2-D Digital Predistortion Model Based on Normalized Polynomial Terms," in 2013 IEEE MTT-S International Microwave Symposium (IMS'2013), Seattle, WA, USA, 2-7 June 2013.
16. M. F. Younes, A. Kwan, M. Rawat and F. M. Ghannouchi, "Three-Dimensional Digital Predistorter for Concurrent Tri-band Power Amplifier Linearization," in 2013 IEEE MTT-S International Microwave Symposium (IMS'2013), Seattle, WA, USA, 2-7 June 2013.
17. X. Chen, W. Chen, F. M. Ghannouchi and Z. Feng, "A Novel Design Method of Concurrent Dual-Band Power Amplifiers Including Impedance Tuning at Inter-Band Modulation Frequencies," in 2013 IEEE MTT-S International Microwave Symposium (IMS'2013), Seattle, WA, USA, 2-7 June 2013.
18. O. Hammi, M. S. Sharawi and F. M. Ghannouchi, "Generalized twin-nonlinear two-box digital predistorter for GaN based LTE Doherty power amplifiers with strong memory effects," in 2013 IEEE International Wireless Symposium (IWS'2013), Beijing, China, pp. 1-4, 14-18 April 2013.

19. Z. Lu, W. Chen and F. M. Ghannouchi, "High-efficient Harmonic-Tuned Power Amplifier With More Than an Octave Bandwidth," in 2013 IEEE Wireless and Microwave Technology Conference (WAMICON'2013), Orlando, FL, USA, pp. 1-3, 7-9 April 2013.
20. R. Darraji and F. M. Ghannouchi, "High Efficiency Doherty Amplifier Combining Digital Adaptive Power Distribution and Dynamic Phase Alignment," in 2013 IEEE Wireless and Microwave Technology Conference (WAMICON'2013), Orlando, FL, USA, pp. 1-3, 7-9 April 2013.

Books and Book Chapters

1. A. Hasan, M. Helaoui, and F. M. Ghannouchi, "Subsampling Multi-Standard Receiver Design for Cognitive Radio Systems" in White Space Communication Technologies, Cambridge University Press, 2014.

Special/Invited Presentations:

1. Professor F. M. Ghannouchi as a Distinguished Microwave Lecturer gave an invited talk entitled "Power Amplifier and Transmitters for SDR applications" at the 2013 International Microwave and RF Conference (IMaRC'2013), New Delhi, India, on December 14, 2013
2. Professor F. M. Ghannouchi as a Distinguished Microwave Lecturer gave an invited talk entitled "Sustainable Communications" at University of Alberta, Edmonton, on November 18, 2013.
3. Professor F. M. Ghannouchi as a Distinguished Microwave Lecturer gave an invited talk entitled "Green and Sustainable Communication Networks" at University of Alberta, Edmonton, on November 18, 2013
4. Professor F. M. Ghannouchi as a Distinguished Microwave Lecturer gave an invited talk entitled "Communication Radios" at Chalmers University of Technology, Gothenburg, on November 13, 2013
5. Professor F. M. Ghannouchi as a invited speaker gave an invited talk entitled "Power amplifiers for 5G technology" at ZTE Research Center, Xi'an, China, on October 24, 2013.
6. Professor F. M. Ghannouchi gave an invited talk entitled "Advanced Transmitter architectures" at Beijing Posts and Telecommunications University, Beijing, China, on October 23, 2013.
7. Professor F. M. Ghannouchi as a Distinguished Microwave Lecturer gave an invited talk entitled "Advanced Transmitters for SDR applications" at Tsinghua University, Beijing, China, on October 21, 2013.
8. S. Rezaei as an invited speaker gave a talk entitled "1.5 GHz – 3 GHz, 10W, 60% Efficiency Class-J PA for Cognitive Radio Applications" at the International Midwest Symposium on Circuits and Systems (MWSCAS'2013), Columbus, Ohio on August 4-7, 2013.

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 those discussed in the following paragraphs.

The iRadio Lab hosted the University of Calgary university booth at the IEEE International Microwave Symposium 2013 (IMS'2013), held in Seattle, WA, USA. Among the demonstration 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 suns, planets and a galaxy, sponsored by the IEEE student branch. Selected members were 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 in this year. This spreadsheet is attached with this report.

Funding Sources:

- 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