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) in the Department of Electrical and Computer Engineering of the Schulich School of Engineering at the University of Calgary. Following the research program's successful achievements, a renewal of the Chair was granted by Alberta Innovates Technology Futures (AITF) for an additional five-year period starting May 1st, 2011 and extended upon the request of the Chair holder to April 30, 2018.

The present research program is a continuation and reinforcement of the research and development (R&D) activities conducted at iRadio Lab during its last ten-year period. These activities have led to the recognition and positioning of the University of Calgary as an emerging world-class research institution in the area of RF (radio frequency) radio systems. The main objective set for iRadio Lab's second mandate is the building on the success of past achievements to seamlessly align the R&D activities toward gigabit (Gbit) software-defined radio (SDR), green communications and multiple-input multiple-output (MIMO) and multi-antenna (MA) systems. The planned research program for this second mandate is centered around the development of relevant and enabling technologies for 5G (5th generation) wireless communications and Internet of Things (IoT) related microwave and millimetre-wave (mm-wave) devices, circuits and systems, Gbit digital and mixed electronics, adaptive digital signal processing, modeling of devices, channels and systems, linearization and equalization concepts, space diversity techniques and MIMO and MA systems, software-hardware implementation and integration issues, design and realization of circuits and systems with hybrid and integrated technologies, and other related applications.

iRadio Lab is already staffed with more than twenty-five graduate students and researchers, who have been recruited from around the world. The main space dedicated to iRadio Lab is in the University of Calgary's ICT building (ICT 305 and ICT 318) and is being used as offices for graduate students and research staff, as well as the research program's main instrumentation, simulation and design area. An auxiliary space in A Block of the Engineering Building (ENA 5) is also being utilized by graduate students and researchers for printed circuit board fabrication, prototyping and storage of newly procured equipment for the Canada Foundation for Innovation (CFI) funded mm-wave facility, until space can be allocated by the department for this new facility. This new mm-wave facility is composed of the latest, state-of-the-art signal generation and analysis equipment (up to 2 GHz bandwidth modulated signals) and offers the capabilities of ultra-wideband on-wafer measurement capabilities at mm-wave frequencies (up to 67 GHz).

Leading-edge research, development, testing, validation and evaluation of new concepts and architectures relevant to software-defined and software-enabled RF radio activities are being conducted in collaboration with the RF and wireless communications industry and government R&D agencies. iRadio Lab has close, formal collaborations with several national and international academic institutions, industry partners and government agencies.

The innovative and application-oriented R&D activities being carried out at iRadio Lab in this past year have led to 17 refereed journal papers (published and accepted), 31 refereed conference papers (published and accepted), 8 patent applications, 5 US patents allowed and the publication of two book chapters. Three keynote and invited talks were given by iRadio Lab researchers at international conferences and leading research institutions and universities. A Ph.D. student, Tushar Sharma, was awarded an AITF-ICT scholarship; and, a second Ph.D. student, Andrew Kwan, was the recipient of an NSERC (Natural Sciences and Engineering Research Council of Canada) Ph.D. Award. A third PhD student, Xiang Li, was the recipient of an AITF Doctoral Award for Chinese Students.

During its eleventh's year, iRadio Lab was successful in securing funding amounting to $88 K, $200 K and $150 K from NSERC, Canada Research Chairs (CRC) program and the University of Calgary, respectively. In addition, in-kind contributions and equipment donation in the amounts of about, $100 K from CMC, and $200 K of in-kind contributions from the University of Calgary have been obtained during the reporting period. Furthermore, many students and postdoctoral fellows have been awarded scholarships and fellowships over the last year, totalling an annual of $448 K.

2. RESEARCH PROGRAM OVERVIEW

The Research Team

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

Research Partners

iRadio Lab has been mainly funded by the joint sponsorship of AITF, CRC, NSERC and CFI. Formal academic collaborations are maintained with Canadian and international universities in the areas of device- and system-level modeling, power amplifier design and optimization, and software-defined radio based transceivers. In addition, close collaborations have been made with major leading national and international companies and agencies.

Major Research Directions

The scope of this AITF/CRC research program is related to the development of intelligent and green RF radio systems for next generation wireless communications, sensors networks and IoT at large. The main goal is the development of software-defined, high-performance, environmentally friendly transceivers. This multidisciplinary research calls for broad knowledge in the fields of digital signal processing (DSP), mixed signal technology and microwave and mm-wave technology and communications systems, including the manufacturing processes and implementation in the respective fields. The ongoing research activities span over the research directions that were identified in the Chair's renewal proposal.

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

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

Green microwave technology: The power amplifier (PA) is the most critical and expensive subsystem in all RF wireless systems, as its performance significantly affects the overall performance of the transmitter, in terms of linearity and power efficiency. Accordingly, the development of power-efficient PA modules used in advanced transceiver architectures is essential for any high-performance, environmentally friendly (green) transceiver design in hybrid and/or integrated technologies.

DSP for communications: The advances in transceiver architectures call for an RF/DSP co-design approach, in order to ensure the desired functionality and optimal system-level performance. This includes impairment pre-compensation and architecture-dependent signal processing and conditioning.

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

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

Millimetre wave (mm-wave) electronics: With the increasing demand for high data rates, Gbps (gigabit/second) communication has become a necessity in recent years. Such speeds cannot be achieved by transceivers with carrier frequencies located in the lower frequency bands, such 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 Harvesting and Recycling: The appeal of energy harvesting either as an auxiliary power source to recharge battery or as a primary source in self-powered sensors applications has drawn significant research attention. In order to reduce operating costs and minimize the impact of the carbon emission footprint of communication networks, but still reach the full potential of IoT, many wireless infrastructure providers and operators have been highly active in the investigation of new approaches and techniques to reduce energy consumption and /or recycle energy dissipation within the RF front-end and sensors with the aim to develop power efficient (green), self-sustainable and ultra-low-power consumption radio and sensors that are capable of harvesting their required energy from ambient sources from the presence of electromagnetic communication systems in the usage of wireless communication devices.

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: Recently, continuous SMPAs, such as continuous Class-F mode and continuous inverse Class-F, were designed to improve the bandwidth while maintain constant high efficiency and constant output power. With this concept, it is possible to move the fundamental and second (or third) harmonic load impedances properly without changing the efficiency and output power in the PA design, which highly improve the design flexibility. However, these continuous SMPAs need to fix the third (or second) load impedance to short-circuit or open-circuit in the design space, which is impossible in practical broad band PA design. Mode transferring method was proposed to move the second and third harmonic terminations simultaneously. However, only two transient state, Class-F mode and inverse Class-F mode, are identified in this transferring process. There is no theoretical current and voltage waveform expressions for other transient state in this transferring process. Thus, mode transferring can optimize the efficiency at two transient state instead of the whole bandwidth, which leads to non-constant efficiency and output power. To solve this problem, a generalized continuous SMPA is proposed. The theoretical voltage and current waveforms are established for varying first three harmonic load impedances. It is possible to maintain constant high efficiency and constant output power by varying the fundamental, second and third harmonic impedances properly. To validate this theory, a Cree's 10 W GaN transistor was used to design a broadband SMPA. The fabricated PA performed a high efficiency above 60% over 63% fractional bandwidth (from 1.3GHz to 2.5GHz) under CW test.

Continuous-mode PAs: In contrast to the conventional continuous mode power amplifiers (CMPAs), we propose an approach that provides a "contiguous" set of design spaces (i.e., multiple impedance trajectories) for a specified power-efficiency. The design methodology establishes a correlation between harmonic and fundamental impedances, thereby offering a greater control over the harmonic tuning. The multiple voltage/current waveforms solutions overcome the complex matching problems by enabling more flexible selection of impedances to PA designers. The proposed methodology is validated using a 1-Watts gallium–nitride transistor and provides state-of-art performance with peak drain efficiencies greater than 75% measured over carrier frequencies between 500 and 900 MHz i.e. (57% fractional bandwidth). The saturated output powers, on the other hand, are higher than 10 Watts with a maximum of 13 Watts. The work is reported in *IEEE Transactions on Circuits and Systems II*

Moreover, the applications of the continuous-mode concept are also extended to class AB and class C bias condition. The new model provides fundamental and corresponding second and third harmonic impedances at all bias conditions. Since, the resulting design space becomes the function of gate voltage bias, this enables the application of CMPAs in advanced efficiency enhancement architectures that demands PAs operating at classes other than B class. The work is implemented using GaN technology and was reported for the first time in *IEEE Microwave and Wireless Components Letters*. Since most of advanced PA/transmitter architectures (e.g., Doherty, Outphasing, Delta-sigma, etc.) require using PAs that are operated at classes of amplification different that the class B, CMPAs for class AB/C bias condition will help in increasing deployment of these broadband PAs in RF front ends.

Green RF Power Amplification Systems

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

Broadband Doherty PAs: In Doherty amplifiers, the impedance transformer of the output combining network is a critical component that limits the bandwidth of the Doherty PA. To solve this issue, the design of an impedance transformer with wideband, maximally flat real-to-real impedance matching was investigated. The design formulas for two-section quarter-wave transformer were presented and exact solutions for transmission lines' parameters are derived in explicit form for any impedance transformation ratio. The results of this study are useful for realization of broadband Doherty amplifier circuits. To validate the proposed design formulas, three impedance transformers terminated in a fixed impedance of 50 Ω and three target impedances of 100, 150, and 200 Ω are fabricated and measured. Measurements show a good agreement with theory and simulations.

The proposed structure was then exploited to design a high efficiency Doherty power amplifier. In theory, this power amplifier can achieve a fractional bandwidth of 80% with high dc-to-RF conversion efficiency at power back-off. A prototype of this Doherty PA was fabricated and is currently being tested. Initial results with continuous wave showed more than 45% drain efficiency at 6 dB output power back-off over the frequency band ranging from 500 to 900 MHz.

Multi-band Doherty PAs: Multi-band Doherty PAs were developed since high efficiency broadband PAs are not able to cover very wide and contiguous frequency band. Recently, various dual-band, tri-band and quad-band Doherty PAs were designed. However, the reported quad-band Doherty PA can only operate at specific frequencies. To improve the design flexibility, a quad-band Doherty PA based on T-shaped coupled line network (TCLN) is proposed. With TCLN, the quad-band transmission lines and quad-band power amplifiers are realized at three arbitrary frequencies and the fourth is related to the design selectable three frequencies. The ratio of the highest operating frequency to the lowest operating frequency covers the range of 1.95 to 7, while the ratio of the other two operating frequencies fall in the range of 1.3 to 2.76. Finally, a fabricated quad-band Doherty PA reaches peak efficiencies of 67.9%, 52.7%, 73.1% and 66% and 6 dB back-off efficiencies equal to 54.6%, 44.6%, 58.9% and 51.4% with maximum output power of 42.3, 42.4, 42.5 and 41.7 dBm at 0.73, 1.65, 2.67 and 3.57 GHz, respectively.

Load-modulated PA Structures: The load modulated power amplifiers are usually used to boost the efficiency for high PAPR communication signals. The Doherty amplifier is one of the most well-known load-modulated power amplifier structures for achieving high efficiency for wireless transmitters. The impedance inverter in Doherty structure is usually considered as a limiting factor in achieving broadband operation. Previously, the TLLM amplifier structure and the Doherty structure with three-port input/output networks were proposed at iRadio Lab to mitigate the bandwidth limitations of the Doherty structure. These proposed amplifiers use the same multi-branch structure as the Doherty amplifier. In these amplifiers, a class AB amplifier branch is used along with a class C amplifier branch to achieve the load modulation and high efficiency at power back-off.

Recently, a new biasing technique has been proposed at iRadio Lab. In the new biasing technique, a constant current source is used instead of conventional voltage source. Using a current biasing, the power amplifier transistor presents completely different and new characteristics compared to the conventional voltage-biased transistors. One of the different characteristics of a current-biased transistor is the reverse load modulation (compared to a voltage-biased transistor). This behavior was used in a multi-branch amplifier structure to achieve high efficiency for very large bandwidths. The proposed structure utilizes a current-biased amplifier branch along with a voltage biased amplifier branch to achieve proper load modulation without using the impedance inverter of Doherty amplifier. A prototype of the proposed amplifier was fabricated and tested. The measurement results showed that the proposed amplifier structure can achieve high efficiency in bandwidths larger than one octave. A paper describing the proposed amplifier structure, proposed design procedure and the measurement results obtained from the prototype has been submitted to IEEE Transactions on Microwave Theory and Techniques.

Advanced Adaptive DSP Algorithms for Wireless Transceivers

Transmitter digital domain linearization solutions are constantly evolving to extract optimum benefits in terms of cost, performance and flexibility. The current and futuristic trends in the arena of transmitter system modeling and digital domain compensation for Radio frequency distortions of nonlinear power amplifiers and wireless transmitters are presented in this section. The effects of the modulator imperfections, such as gain and phase imbalances, phase errors, and DC offsets and their effect on the feedback loop of a digital predistortion system, are analyzed in the case of single-input single-output (SISO) transmitters, which is further extended to multi input-multi output (MIMO) systems. Indeed, the effects of RF imperfections are more pronounced in MIMO transmitters, whereas many PAs are mounted on a chip and separate communication channels are used for each radio path. Hence, in addition to the RF impairments of SISO case, the RF coupling and cross-talk-effect of the parallel PA paths and different radio-channels should be compensated for as well.

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

MIMO Transmitters To keep up with the explosive increase in user demand for higher data rates while maintaining signal quality, multiple-input multiple-output (MIMO) architectures are being increasingly adopted by the wireless communication industry (for example, the current fourth-generation systems allows for 4x4 MIMO at the downlink.

Capitalizing on the potential of MIMO in increasing the capacity of the networks and the data rates, the upcoming fifth-generation (5G) standard adopts large-scale MIMO (known as Massive MIMO) as a core part of its architecture, with MIMO systems of up to 256x256 MIMO being considered (with physical prototypes having been successfully built in Sweden and South Korea). The use of Massive MIMO, however, is not without its issues as the large-scale integration and limited isolation between MIMO transmitter paths inevitably leads to leakage and interactions between the various signal paths. This phenomenon is known as crosstalk, which can occur either before the PA (nonlinear crosstalk) or after the PA (linear crosstalk). Typically, the crosstalk and PA nonlinearity are jointly compensated for by utilizing 2x2 digital predistortion (DPD) in a 2x2 MIMO transmitter, which is associated with high computational and implementation costs. Furthermore, all of the research efforts to date have focused on addressing the linearization of MIMO transmitters in case of weak (or low) crosstalk, which is a major issue as the crosstalk in realistic MIMO systems is often quite significant, especially with the high levels of integration proposed for the upcoming fifth-generation systems which use large-scale MIMO. To address this crucial shortcoming, a novel DPD model which is suitable for a wide range of crosstalk scenarios ranging from weak to very strong has been proposed. This model was found to combine the low computational cost of the simple single-input models with the high performance of the costly two-box models. The performance of this model was shown to greatly exceed that of the benchmark models, and the results have been recently published in IEEE Transactions on Communications. Furthermore, a technique for de-coupling the crosstalk and canceling it without the use of 2x2 DPD is currently under investigation.

Transceiver Hardware Impairments: The digital domain linearization/correction of different RF imperfections are important for improving the performance of transceivers. The PA is the most nonlinear and energy consuming device in any conventional transmitter and the main source of intermodulation distortions. These nonlinear distortions cause spectral regrowth and the signal might fail to meet the spectral mask requirements set by the telecommunication authorities. However, there are other imperfections in transceivers that limit their performance considerably. These include, the nonlinear effects of the low-noise amplifier (LNA) in the presence of strong blockers. This effect is even more pronounced for software defined radios, which do not have a band-pass filter before the LNA. In this case, the blockers pass directly to the LNA resulting in intermodulation distortions. Other major RF impairments, such as in-phase / quadrature (I/Q) imbalance, phase noise (PN) and carrier frequency offset (CFO), result in various problems and make the detection of the signal difficult at the receiver, along with degrading the bit error rate. The antenna and non-constant group delay variations in band-pass filters also cause distortions. IQ imbalance and DC offset deteriorates the signal quality at the output of the transmitter chain and affects the EVM. It is important, therefore, to alleviate these imperfections with reduced complexity algorithms. The transmitter can be calibrated and these impairments can be pre-compensated in digital domain. A memory polynomial model with conjugate terms is used to model these imperfections. The model is implemented on a FPGA based SDR platform and the performance of the linearized transmitter is evaluated using modern communication signals.

The joint effects of both the transmitter's and receiver's imperfections can be eliminated at the receiver using post compensation algorithms. For this purpose, the effects of the wireless channel are also considered when formulating different methods to correct the aforementioned imperfections. Post-compensation methods led to reduced transmitter complexity from both hardware and software perspectives. Simulations of the combined distortions and impairments effects of the transmitter, channel and receiver have been carried out and appropriate pre-compensation at the transmitter side and post-compensation at the receiver side algorithms to mitigate these unwanted effects are under development. Signals with high Peak to Average Power Ratio (PAPR) drives the power amplifier into the nonlinear region resulting in intermodulation distortions. Hence, the PA has to be operated at back-off to behave linearly resulting in reduction of the power efficiency. If the PAPR of the signal is reduced a lesser back-off is required and the PA can still operate at a relatively higher efficiency. However, PAPR reduction schemes can also lead to nonlinearity. Recently, an optimization based method for a polynomial based clipping method was introduced to reduce the PAPR and a post compensation technique was used to eliminate the resulting nonlinearity. Currently, blind compensation of transmitter's and receiver's I/Q imbalance is being carried out in the presence of noise. In addition, blind compensation of the combined effect of both the modulator's imperfections in the presence of PA nonlinearity is being studied.

Software Defined Radio (SDR) Transmitters

The research activities focusing on the Software Defined Radio (SDR) transmitters have been conducted within a collaboration with the Ericsson Canada research team and was supported by an NSERC Collaborative Research grant and AITF funds.

The software-defined radio technology has the feature to control the RF characteristics of the transceiver based on software reprogramming. This is possible by the substitution of all the analog RF components limited in bandwidth with the equivalent digital forms. The use of Delta-sigma modulators (DSMs) will enable the conversion of the normal low-speed baseband signal into a high-speed pulses, where changing the pulses speed sets the desired transmitted frequency band. Utilizing these bi-level pulses followed by high-efficiency SMPAs (switching-mode power amplifiers) can boost the overall efficiency of the transmitter to its maximum. The use of multi-level signals instead of a bi-level has a potential to generate a better signal quality. An improvement of this topology based on RF digital-to-analog converters (RFDACs), where the normal frequency mixing is replaced with digital components in order to reduce the distortion and noise at the output of the transmitter while allowing for reconfigurability.

All-digital Delta-sigma Based Transmitter: A novel dual branch (Delta-Sigma) based on a multiplexer was used to perform the up-conversion instead of using an analog up-converted limited in bandwidth. The multiplexer can be controlled by software to adjust the carrier frequency. This topology is simulated and implemented in order to validate the throughput of a multi-standard DSM by increasing the parallelization as well as increasing the number of levels of the output signal. Techniques for noise quantization level reduction can significantly enhance the coding efficiency of the DSM Transmitter (DSM Tx). For up-conversion to RF frequencies, a multiplexer is used at the output of the DSM Tx. This up-conversion technique requires a high speed clock (10 GHz) and offers more flexibility and a wide range of carrier frequencies (10 MHz - 2.5 GHz). The transmitter was tested using a continuous wave signal and an LTE signal with a bandwidth of 5 MHz. A full transmitter that integrated both an SMPA stage and a band-pass filtering stage was tested and validated. The measured results are in accordance with the predicted simulation results in terms of adjacent channel power ratio (ACPR) and coding efficiency compared to those of the single-branch topology. The parallel processing in this topology is implemented by using high-speed platform which enabled the DSM Tx to handle larger bandwidth signals.

Hardware Integration of a Complex Delta-sigma Transmitter: Three-level complex delta-sigma modulator (DSM) topology that uses an adaptive noise suppression technique was proposed. The performance of this architecture in terms of bandwidth, power efficiency and coding efficiency are considerably improved, as compared to Cartesian modulators. The complex DSM transmitter was implemented on a FPGA based SDR platform from National Instruments. The transmitter impairments, IQ imbalance and DC offset were modeled and pre-compensated digitally in the FPGA. The transmitter outputs of the 2x2 MIMO system were fed to two class-E RF power amplifiers (6W and 25W connected back to back). The complete architecture was evaluated using an LTE signal with a bandwidth of 1.4 MHz. For an average output power of 32 dBm, a coding efficiency of 72% and an in-band efficiency of 31% were obtained.

Complex Delta-Sigma Based Transmitter with Enhanced Linearity Performance Using Pulsed Load Modulation Power Amplifier: A linear and efficient transmitter prototype based on pulsed load modulation (PLM) power amplifier (PA) was proposed. The proposed transmitter setup utilizes the complex delta-sigma modulation as a signal processing technique instead of the envelope delta-sigma modulation for higher linearity performance. Using the complex delta-sigma modulation technique reduces the in-band quantization noise significantly at the output of the modulator and consequently, enhances the linearity of the transmitter. To validate the proposed technique, the linearity and efficiency performance of the complex delta-sigma modulator (CDSM) based transmitter was compared with the performance of its envelope delta-sigma modulator (EDSM) counterpart in measurement. For this study, an efficient and linear PLM PA was designed and fabricated using GaAs E-pHEMT transistors. The proposed architecture was tested with LTE uplink signal. For an LTE uplink standard signal with 3 MHz bandwidth and 7 dB PAPR, the complex delta-sigma modulation based transmitter achieved the drain efficiency and PAE of 46% and 42%, respectively, at an average output power of 25.1 dBm. The comparison measurement study of EDSM based transmitter and the CDSM based transmitter with LTE uplink signal showed about 11 dB improvement in the SNDR of the output signal. The measurement results for LTE signals were able to pass the spectral requirements defined by the standard without applying pre-distortion techniques.

Three-way Envelope Modulator Based RF Transmitter for Wideband Applications: A new RF transmitter architecture that uses only envelope modulators was proposed. The baseband phase signal is up-converted to RF without the use of mixers and quadrature up-converters. As a result spurs and distortions associated with switching circuits are avoided and no RF filtering is required at the output. The absence of an RF band-pass filter eliminates the operating frequency constraint and makes the transmitter design reconfigurable and more integrated. A new modeling technique is adopted for compensating the transmitter impairments in digital domain. The hardware implementation of the transmitter is realised using evaluation boards and the performance in terms of signal quality is tested using 3GPP signals.

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

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

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

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

Adaptive and Tuneable Receivers

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

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

Subsampling Receivers: In conventional RF receivers, a down-conversion stage is used to translate a RF signal into a baseband that is suitable for demodulation. For multi-band radios, the common approach is to design each receiver to target a specific RF receiver band, where the size of the radio proportionally increases as the number of bands increases. Subsampling (or bandpass sampling) is a technique which intentionally aliases the RF components into a lower frequency, where a low speed ADC may be used. With this technique, a single RF subsampling receiver stage can be used for multi-band signal reception, and multiple down-conversion stages are unnecessary.

The increase in wireless technology for biomedical applications has led to allocation in specific spectrum bands up to 3 GHz. To minimize the number of RF receivers needed for these kind of applications, a broadband subsampling receiver is proposed. Recently, this technique has been used for software defined radio (SDR) applications to allow multiple and concurrent RF signal digitization directly from the RF stage by using a sampling frequency much lower than the RF frequency. An efficient subsampling algorithm is proposed to determine the sampling frequency needed such that interferences between the different monitoring and sensing medical signals is mitigated. Measurement results are provided with RF instrumentation equipment and a low speed ADC to validate the proposed architecture for a quad-band monitoring and sensing application.

Ultra-wideband Six-port Based Direct Conversion Receivers: Very accurate signal processing algorithms for ultra-wideband six-port based direct conversion receivers that had been developed were computationally complex. Another calibration approach for six-port based direct conversion receiver was developed that was less computationally involved while providing the similar or better performance when tested with the previously used ultra-wideband (UWB, 2-18 GHz) receiver prototype. The traditional six-port based receivers employ diode based power detectors in their architecture that are known to have very low sensitivity and selectivity, and very high noise figure performances. Previous research works carried out in our lab had addressed the issues of non-idealities of the components and system of the existing six-port based receiver systems. Research is in progress to address the issues of sensitivity, selectivity and noise figure by proposing a completely novel and new architecture for the multi-port based receiver. Initial simulation results have shown very promising results. Prototype design for this new proposed architecture for multi-port based receiver system is in progress and very soon we will have a completely functional multi-port receiver system with improved sensitivity, selectivity and noise figure measurement metrics.

Modeling and Impairments Compensation in Six-port Receivers: Six-Port receiver, as an important zero intermediate frequency receiver, can be easily integrated and fabricated for wideband applications because it is based on the passive components and diode detectors. The performance of the six-port receiver can be improved greatly by the use of appropriate signal processing based calibration algorithms.

Many different algorithms, which include dual-tone calibration and self-adaptive algorithm, two-step calibration, real-time calibration for solving eight linear equations, the calibration based on three and four signal standards, auto calibration using several digital channelization, and calibration based on the equalizer, have been proposed to retrieve the in-phase and quadrature signals from the originally transmitted radio frequency signal. However, none of the above algorithms takes into account all the system imperfections, such as the direct current (DC) offset, the non-ideal six-port correlator frequency response, the nonlinearity of the diodes, and the memory effects under the excitation of the wideband signals.

Hence, a novel calibration algorithm based on the real-valued time-delay neural network (RVTDNN) was proposed to improve the accuracy of the received signals. This RVTDNN is new approach for modeling and calibration of a six-port based receiver system that takes into account all the previously reported non-idealities and impairments of a six-port based zero-intermediate frequency receiver. This newly proposed method improved the overall performance of the six-port based receiver system with similar or less complex signal processing based calibration approach reported previously.

Multiband and Multimode SDR-Based Transmitters

Software defined radio (SDR) technology brings the flexibility, cost efficiency and power to drive communications forward, with wide-reaching benefits realized by service providers and product developers through to end users. Since, the strategy of increasing data rates in a single carrier configuration is starting to plateau as we progress toward Shannon's capacity theorem. Analogous to adding more cores in a processor, the easiest way to increase capacity is to utilize multiple bands for signal transmission. However, these bands are typically separated by a band gap reserved for other wireless applications. Concurrent multiband transmission is especially important in the next generation of LTE Advanced (LTE-A) standard in either inter-band or intra-band carrier aggregation configurations.

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

Linearization of Broadband Transmitters: In order to service more users simultaneously and ensure backwards compatibility between the different generations of wireless networks, service providers are growing more reliant on the use of multi-band and carrier aggregation (CA) techniques. However the wide bandwidths and frequency separations employed often means that it is not possible to correct the resulting third-order intermodulation (IMD3) distortions; as they will fall at frequency bands which are located far away from those of the carrier bands; thus making the hardware cost of capturing the IMD3 and correcting it rather prohibitive. The IMD3 issue has been one that has continuously plagued the multi-band linearization research community since the inception of multi-band DPD techniques. To date, it has been addressed by capturing the IMD3 signals at the output and then feeding them back (i.e. injecting them) to the input of the amplifier/transmitter. However, this means that for a dual-band system, four receivers are needed instead of just two, and two additional full feedback loops would be required and thus rendering this approach to be prohibitively expensive. To help in resolving this core issue, a method was proposed which uses mathematical modeling techniques to predict the IMD3 components to be injected at the amplifier input instead of capturing them at the output, which circumvents the need to deploy the additional receivers at the output while maintaining the concept intact. This technique was shown to achieve substantial performance in reducing the level of IMD3 distortions without the need for capturing/sampling at the output and a paper based on the concept is currently undergoing review in IEEE Transactions on Microwave Theory and Techniques.

A technique for compensating the nonlinear distortion of closely spaced multicarrier power amplifiers is proposed, which is applicable for intra-band carrier aggregation. Hence, the proposed DPD with constrained feedback bandwidth is based on a multi-stage architecture. By extracting the PA static characteristic parameters from the bandwidth-constrained signals, and separately processing the multi-carriers input, the proposed DPD reduces the feedback bandwidth and hence the sampling rate. Moreover, it effectively suppresses the spectral regrowth within the off-carrier regions along the submitted bandwidth, not only the adjacent channels. The proposed method can significantly decrease the difficulties in system design and reduce implementation cost.

Envelope Tracking for Multiband Transmitters: Envelope tracking (ET) power amplifiers enables high efficient operation at low output back-off power levels by changing the voltage supplied to the PA. The dynamic voltage operation is based off the RF envelope characteristics, and can be shaped to provide a more efficient amplifier operation. However, the consequence is a highly nonlinear response compared with a fixed voltage supply. The PA characteristics are highly nonlinear when using ET, where a high complexity model is required to model the ETPA behavior. Subsequently, the model complexity is similar for the digital predistorter model to compensate for the nonlinearity effects caused by the dynamic voltage changes. One of the accurate PA models is the Volterra model; which can accurately describe a dynamic nonlinear system, but leads to a very large number of coefficients. Compressed sampling is a technique that can be used on the model, which reduces the complexity by removing redundancy and sparsity of the coefficients. With a 4-channel multi-carrier LTE signal, the compressed sampling technique is able to reduce the error of the model while maintaining a low coefficient number.

Since the PA characteristics change from both the voltage and signal supplied to the PA, a dual-input, two-box modeling approach was used to model the ETPA behavior. In a traditional dual-input ETPA model, the two signals supplied are the baseband waveform and the drain voltage supplied to the PA. The proposed architecture involves modeling the static nonlinearity distortions of the PA, and applying its inverse characteristics to the input signal before being supplied to the dual-input model. The experimental validation shows that the proposed two-box model outperforms a single dual-input model, and is able to meet the LTE mask specifications with a 20 MHz LTE signal.

Integrated Circuit Design – Microwave and Millimetre Wave

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

The activities carried out within these projects of integrated designs for microwave and mm-wave applications have been performed in close collaboration with Canadian Microsystem Corporation (CMC), who provided the design kit and measurement setups, technical support and fabrication of the chips. These projects have also been supported through an NSERC discovery grant and AITF funds.

GaN PAs: A recently published theory for Class-J PA using dynamic load modulation (DLM) allows obtaining better broadband performance. This is done by modifying the fundamental load impedance. First, the proposed theory is analyzed and it is observed that the fractional bandwidth can be increased from 36% to 73% by modifying the load impedance. The ideal linear model based on this theory is transferred to a non-linear model, which can be used with realistic transistor models for a more accurate design. To proof this theory, the ideal model is transferred to a circuit simulation and the correlation between both is shown. Then the theory is verified by designing a gallium nitride (GaN) high-electron-mobility transistor amplifier that includes varactor diodes in the output matching network for the load modulation purposes. Simulations show a similar behavior as predicted by the theory, but it is observed that the bandwidth is limited by the tuning range of the varactor's used. Due to losses in the output matching, the measured efficiency is lower than expected. Yet, the amplifier achieves an almost constant behavior over 40% fractional bandwidth. It was observed that the bandwidth and the back-off performance are mostly limited by the tuning range of the varactor diodes. Therefore, it is hard to achieve the theoretical performance with real components. However, using other components, like SiC varactors and air core inductors, could lead to lower losses and therefore to a better efficiency. The proposed modification of the theory shows great potential for practical PA design, with the cost of a more challenging matching networks design, a better performance can be obtained.

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

A Doherty amplifier requires a splitter at the input to provide the input power to both main and peaking amplifiers with a certain power ratio. A symmetric or asymmetric Wilkinson splitter is used to perform the power division task, which is constructed by lengthy-lossy transmission lines. Implementation of such a bulky passive on-chip component is one of the largest challenges in design of on-chip Doherty amplifiers. It is more problematic in low frequencies that the splitter layout can take up approximately half of the chip size. Modification of the design, by removing this part from the circuit design, can considerably alleviate this problem. We proposed a new splitter-less load-modulated PA. The proposed design contains conventional CMOS class-B and class-C amplifiers. The invention is to design class-B amplifier in a way that provides enough gate-source voltage level to the first stage of class-C amplifier to turn it on in the corresponding input power. Using this approach, the bulky-lossy splitter is removed and its functionality is also performed by the amplifiers. We designed the amplifier in 0.13 um IBM CMOS technology. The amplifier was designed to work at 5.2 GHz and the output power at 250 mW or 24 dBm. The simulation results showed an efficiency of about 40% at the maximum output power, while the efficiency in 5 dB output power back-off (OPBO) was 30%. We received the chips, and measurements will soon be undertaken in collaboration with Dr. Belostotski at the University of Calgary.

Millimetre-wave Receiver: 60 GHz band communication is another research drive related to mm-wave communication in the unlicensed band spanning from 57 GHz to 64 GHz, where higher operating frequency and new regulations demand R&D in mm-wave circuits and systems.

Recent research work carried out in our lab in the areas of six-port based quadrature down-conversion have shown the reduced complexity calibration approaches and dual-band approach for innovative implementation and design of wide-band, high-speed, low-cost and low-power wireless transceiver systems. New vector network analyzer (VNA), mm-wave probe station and measurement probes for in-house 60 GHz measurements have been acquired and added to the existing lab facility for mm-wave measurements and characterizations. The new test-setup would allow all the measurements related to a recently fabricated six-port receiver circuit in low-temperature co-fired ceramic (LTCC) technology for the 60 GHz communication band. Measurement is in progress for this receiver front-end circuit that will be used in conjunction with the characterization and calibration algorithms developed for single-band and multiband concurrent radio receiver applications using the six-port technique.

Integrated Active Antenna Systems Miniaturization of antennas is one of the challenging tasks in compact radio frequency (RF) system design. Many different antenna miniaturization techniques available in literature are mainly assuming the interacting impedance to be 50 Ω. But due to the fundamental limit, miniaturized antennas are generally narrowband and likely to be detuned by the output impedance of the power amplifier (PA) or by the input impedance of the low noise amplifier (LNA). Similarly, traditional PAs and LNAs are designed assuming the antenna impedance to be 50 Ω. But when a 10 dB matching is considered, the impedance magnitude can be anything in between 50-100 Ω. Such mismatch at the interface of PA-Antenna or LNA-Antenna not only deteriorates the linearity of the system but also the overall radiation performance by the antenna. To cope with these problems, a new antenna miniaturization technique based on antenna integrated RF front-end is proposed where antenna and amplifiers are co-designed so that optimum amplifier and radiation performances are achieved. The co-design approach is also investigated for an ultra-wideband (UWB) 2×2 MIMO active integrated antenna system which shows more than 10% system radiation efficiency improvement over the operating band. Moreover, to characterize the PA non-linearity behavior under antenna loading, reflection aware PA behavioural modelling is being pursued. Initial obtained results are submitted as a journal paper. Such integrated co-design of antennas and RF front-ends can also effectively realize combiner-less RF systems which are of significant interest for efficient and compact RF system design.

Energy Harvesting: The Internet of Things (IoT) has drawn significant research attention in the last decade, where things refer to interconnected communications devices connected to the Internet without requiring human interactions. Recent projections show that trillions of new sensors will be needed for IoT applications. In order to reduce operating costs and minimize the impact of the carbon emission footprint of communication networks and reaching the full potential of IoT, many wireless infrastructure providers and operators have been highly active in the investigation of new approaches and techniques to reduce energy consumption of radio and sensors with the aim to develop power efficient (green), self-sustainable and ultra-low-power consumption radio and sensors that are capable of harvesting their required energy from ambient sources from the presence of electromagnetic communication systems in the usage of wireless communication devices such as mobile phones, wireless base stations and Wi-Fi hotspots etc. Also, the use of Wi-Fi or Bluetooth connections in residential and industrial places makes the availability of RF signals in the close environment as reliable sources for energy harvesting. For those radios and sensors that are located in areas with less efficient energy sources, a relay node can act as an energy repeater with a capability of bidirectional operation to harvest sufficient power for its own operation, in addition to providing power to surrounding devices and ambient energy sources can help increase battery lifetime through wireless communications and act as a primary source in self-powered sensors. Also, it make the wireless and satellite communications systems reconfigurable on demand, which is expected to be a key technology for 5G wireless communications — the backbone of the upcoming Internet of Things (IoT) aiming at developing smarter, better wirelessly connected and efficiently powered cities.

Energy harvesting sensors consist of an antenna that captures RF energy, a matching network, an RF-to-DC conversion circuit, a DC pass filter and a load. Mainly, two techniques have been perused to remotely power and recharge sensors and enable high-efficiency harvesting: 1) diode rectifiers and 2) synchronous rectifiers based on switching transistors. RF diode rectifier sensors are less complex than synchronous rectifiers, however, synchronous rectifiers can exploit advances in device technology including high efficiency GaN power devices and achieve higher efficient RF-to-DC power conversion. Despite the progress in energy harvesting using synchronous rectifiers in bidirectional systems, maintaining a high efficiency in both operating modes (transceiver and rectifier) raises serious reliability concerns for future communication networks from an energy consumption and harvesting perspectives. This is mainly due to the fact of the narrow spectral operating band of synchronous rectifiers which is preventing widespread adoption of ambient RF harvesting as a power source and also to the possibility of rectifier's cease to operate when faced with single amplitude varying /fading RF source.

Single Band Bi-Directional Synchronous Rectifier: The synchronous rectifier is designed by transforming a class-F/F-1 amplifier into a rectifier using the theory of time reversal duality. Three different scenarios have been studied. In the first scenario, the rectifier is obtained by operating the power amplifier in reverse mode using the harmonic terminations. The power is injected into the drain, with the drain bias turned off and a resistor load connected to the drain bias Tee. A passive tuner is used to provide a wide range of impedances at the gate terminal of the power amplifier. Then the harmonic terminations have been designed such that designed power amplifier operates as a high-efficiency rectifier at the operation frequency of 700 MHz.

In the second scenario, instead of having a harmonics termination, an explicit drain-to-gate feedback is used to properly synchronize the drain and gate waveforms. It provides a gate drive signal from the RF input port and then adjust the phase of the sampled signal to synchronously switch the power device. The results show that the RF-DC efficiency is improved in comparison with the harmonically terminated rectifier with efficiency increasing in the large back off region.

In the third scenario, the effect of second-harmonic loading on the drain-to-gate feedback is investigated. Also, the drain and gate waveforms synchronization in terms of phase and amplitude are studied. Using the second-harmonic control on the feedback, the RF-DC efficiency is increased by 20% on the back off region.

4. OBJECTIVES FOR THE NEXT YEAR

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

Green SDR Transmitters

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

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

New broadband all-digital architectures that take advantage of power-efficient continuous-mode SMPAs will be proposed and implemented to ensure energy efficiency, flexibility/reconfigurability and linear operation over a wide frequency band. New topologies of wireless transmitters using mixer-less RFDACs (RF digital-to-analog converters) will offer solutions that are easily reconfigurable for wide frequency ranges, provide better linearity than state-of-the-art mixer-based solutions, reduce the power consumption compared to switching modulator based mixers, and ensure a higher dynamic range and higher linearity to meet the requirements of 5G wireless communication standards. Avoiding the use of filters along the up-conversion path will provide an overall transmitter solution that is easily integrable with a small footprint at a low cost. These are major features for the next generations of wireless communications, which will use massive MIMO (multiple input, multiple output) and carrier-aggregated 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 systems. The increasing bandwidth results in an increase in distortion and memory effects of the transmitter subsystems. Therefore, more stringent requirements are imposed on the complexity and speed of these signal-processing algorithms. New modeling and model optimization techniques will be sought in order to mitigate these challenges.

MIMO Radio Systems

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

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

Recently proposed DSP algorithms that shield MIMO radios from analog circuit impairments and problems triggered by the proximity of crosstalk between adjacent branches in MIMO radios require high computational complexity that increases exponentially with the number of branches in a MIMO system. Our work on the development of innovative low-complexity algorithms and reduction of the complexity of existing solutions is important in making the implementation of these solutions possible for massive MIMO systems.

DSP for Wireless Communications

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

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

Green Adaptive and Tuneable Receivers

The main challenge in offering an effective solution for the design of adaptive and tuneable receivers is the implementation of a low-cost ultra-wideband (UWB) receiver with minimum impairments in the down-converter, which will be able to effectively remove strong interference. A typical receiver chain calls for the use of a down-converter targeted for a specific RF band and an ADC to reconstruct the transmitted signal. If the down-converter is replaced with a track-and-hold component, the signal can be directly digitized from the RF signal. This technique, called subsampling, allows for a receiver to target different RF signals by changing the clock frequency of the track-and-hold circuit. Initial simulations and measurements have proven the capability of such architecture in receiving different signals. However, it has been proven that this technique increases the thermal noise and aggravates interference-related problems in receivers.

A second architecture for adaptive receivers consists of using a passive multiport network with circuit post-calibration to design a UWB receiver. A proof-of-concept design was assembled to work on a frequency band from 2 GHz to 12 GHz. Dynamic linearization and calibration algorithms able to compensate for the frequency response and the dynamics have been investigated to enable UWB reception capabilities in the six-port receiver. These calibration algorithms allowed a signal-to-noise ratio (SNR) of about 30 dB for the received signals of a bandwidth higher than 10 MHz. Concurrent multi-standard reception using the six-port receiver has been investigated, and it has been shown that the six-port topology is able to concurrently receive two different standards using the same hardware. Multi-standard calibration algorithms were also investigated and were proven to be able to reduce the distortion in the six-port receiver. The effectiveness of these algorithms in the presence of strong interference will be investigated. Modified and new calibration techniques and six-port topologies will be proposed to improve the selectivity of the concurrent band receiver in order to achieve better SNRs. Decreasing the complexity of the calibration procedure will ensure that the implementation of this technique for concurrent tri-band (and above) continues to have reasonable signal processing complexity.

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

Energy Harvesting: Research activities for the next year in this area will focus on (i) the investigation of bidirectional sensors operating in oscillator mode as a wireless power transceiver or in rectifier mode as an energy harvester with a wide input power range in various applications such as environmental technology, industrial electronics and relay infrastructures; (ii) an innovative approach to design a multiband and wideband harvesting systems in which multiple frequency bands are targeted simultaneously with a benefit of 1) RF source flexibility 2) access to additional power and 3) improved sensitivity; (iii) the significant improvements to the sensor's sensitivity to low input power while at the same time increasing the amount of energy harvested over the same time period; (iv) the analysis of harmonic balance and finding the optimal rectifying DC impedances for efficient rectifications; (v) the characterization of the energy harvesting efficiency and output power with a wideband/multiband rectifying element under power optimized waveforms.

The developed bidirectional radio/sensors as a result of this research will be targeted to be highly efficient multiband and wideband radio/sensors in both rectifier and oscillator modes while wideband/multiband harvesting radio/sensors can capture energy across a large swath of spectrum. Also, loss mechanism in the rectifier mode regarding differences in the voltage and current waveforms which is a very important factor in reducing power loss and increasing efficiency will be analyzed. It is expected that the new research output will significantly improve the efficiency of ultra-low RF energy harvesting radio/sensors and contribute to the e-health, home and industrial electronic devices.

5. RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

FACULTY		
Name	Role / Topic	Awards / Special Info
Dr. Fadhel Ghannouchi	Team Leader, Director of iRadio Lab, AITF Professor in Intelligent RF Radio Technology and Canada Research Chair (Tier 1). Research interests are in the areas of microwave instrumentation, modeling of microwave devices and communications systems, design and linearization of RF amplifiers, and SDR and multiband radio systems.	Professor Ghannouchi was selected as a Distinguished Speaker of IEEE-MTT-S Speaker's Bureau. 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. Abu Sesay	Professor Research interests include wireless communications	Dr. Sesay is associated with iRadio Lab
Dr. Abraham Fapojuwo	Professor Research interests include wireless networks	Dr. Fapojuwo is associated with iRadio Lab
Dr. L. Belostotski	Associate professor Research interests include CMOS RFIC transceivers design	Dr. Belostotski is associated with iRadio Lab
Dr. Laleh Behjat	Associate Professor , Research interests include optimization techniques	Dr. Laleh Behjat is associated with iRadio Lab

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

VISITING SPEAKERS		
Name	Topic	Special Info

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

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

Dr. Farid Jolani	Energy Harvesting	Eyes High Postdoctoral Fellow, NSERC Postdoctoral Fellowship

PHD CANDIDATES		
Name	Role / Topic	Awards / Special Info
Anis Ben Arfi	MIMO Impairment Compensation	Graduate Student Productivity Award, President ECE Graduate Students Assoc., Chair IEEE Southern Alberta SIGHT project, SIGHT Award for Design, supervised by Dr. Fadhel Ghannouchi
Mohamed Ammar Al-Masri	Green Communication Networks	Graduate Student Productivity Award, Supervised by Dr. Abu Sesay and Dr. Fadhel Ghannouchi
Mohsin Aziz	Compensation of Transmitter Impairments using Rational Functions	Eyes High International Doctoral Scholarship, Supervised by Dr. Fadhel Ghannouchi
Fatemeh Ghods	Dynamic Spectrum Allocation Techniques	ECE Open Doctoral Scholarship, ECE Travel Grant, FGS Travel Award, Graduate Student Productivity Award, PhD Graduate Excellence Award, Supervised by Dr. Abraham Fapojuwo and Dr. Fadhel Ghannouchi
Abul Hasan	60 GHz Multi-port Receivers	Annual Productivity Award, ECE Graduate Students Travel Award, Open Doctoral Scholarship Award, supervised by Dr. Mohamed Helaoui
Abubakr Hassan Abdelhafiz	Wideband Power Amplifier Characterization and Linearization	ECE Dept Award (Top 20 Student); Graduate Student Productivity Award (x3); Best Research Abstract Award, supervised by Dr. Fadhel Ghannouchi and Dr. Laleh Behjat
Maryam Jouzdani	Digital Transmitters using Pulse Load Modulation	ECE Special Scholarship Award, Graduate Student Productivity Award, supervised by Dr. Fadhel Ghannouchi
Andrew Kwan	Multi-band Envelope Tracking Transmitters	AITF Bill Bridger Award of Excellence, AITF Scholarship, Graduate Studies Travel Award, NSERC Alexander Graham Bell Graduate Scholarship – Doctoral, ECE Open Scholarship Award, supervised by Dr. Fadhel Ghannouchi
Xiang Li	Multi-Band Power Amplifier Design	Supervised by Dr. Mohamed Helaoui
Imen Mrissa	LTE Transceiver Design	Visiting Ph.D. student, INRS, Université du Québec
Tushar Sharma	Digital Doherty Transmitters	Izaak Walton Killam Memorial Scholarship Award, Government of Canada Volunteer Service Award, Letter of Recognition from Hon Kent Hehr MP, Supervised by Dr. Fadhel Ghannouchi
Yulong Zhao	Doherty Based MIMO Active Antenna Systems	AITF Futures Award, University Technologies International Fellowship,

		Eyes High International Doctoral Scholarship, Supervised by Dr. Fadhel Ghannouchi
Mahmood Rajab Noweir	Mm-wave Multi-mode Receivers	Supervised by Dr. Fadhel Ghannouchi
Sagar Dhar	Active Phased Array Antenna	Productivity Award, Supervised by Dr. Fadhel Ghannouchi
Weiwei Zhang	Visiting Student – China Scholarship Council student	Supervised by Dr. Fadhel Ghannouchi

MSC CANDIDATES		
Name	Role / Topic	Awards / Special Info
Sichong Li	RF Power Harvesting	Supervised by Dr. Rushi Vyas and Dr. Fadhel Ghannouchi
Mahmud Hasan	Frequency Based Predistortion of RF Power Amplifiers	Supervised by Dr. Fadhel Ghannouchi
Hosein Taghavi	CMOS PA Design	Research Productivity Award, supervised by Dr. Fadhel Ghannouchi
Milad Tajvidi	MIMO Antenna Beamforming	Supervised by Dr. Fadhel Ghannouchi
Suhas Illath Veetil	RF Digital to Analog Converters	Supervised by Dr. Mohamed Helaoui
Dongming (Mike) Wang	Wireless Channel Modeling	Supervised by Dr. Fadhel Ghannouchi
Aparna Bhardwaj	Adaptive Transmitter's Impariment Compensation	Supervised by Dr. Fadhel Ghannouchi
Jatin Chatrath	Three way amplitude modulator based transmittter	Supervised by Dr. Fadhel Ghannouchi
Raul Amipour	Visiting Student – University of Stuttgart	Supervised by Dr. Fadhel Ghannouchi
Md Ayatullah Maktoomi	Visiting Student - IIITD	Supervised by Dr. Fadhel Ghannouchi
Samarth Saxena	Visiting Student - IIT	Supervised by Dr. Fadhel Ghannouchi
Antoine Gros	Visiting Grad Student – ENSEIRB-MATMECA	Supervised by Dr. Fadhel Ghannouchi

OTHER TEAM MEMBERS (ASSOCIATES, UNDERGRADUATE STUDENTS, SUPPORT STAFF)	
Name	Role / Topic
Abul Hasan	Lab Manager
Andrew Kwan	Lab Manager
Chris Simon	Technical support
Caron Currie	Administrative support to Dr. Ghannouchi and the iRadio Lab team

6. COLLABORATIONS

National Collaborations	
Participants	Nature of Collaboration
École Polytechnique de Montréal: Dr. K. Wu Dr. C. Akyel	Collaboration with the Poly-Grames Research Center (Dr. K. Wu) concerns access to advanced printed circuit board (PCB) fabrication facilities by the iRadio Lab team.
Université de Québec: Dr. A. Kouki	The ongoing theme of collaboration is related to LINC-based amplifiers and GaN transistor modeling.
International Collaborations	
Participants	Nature of Collaboration

New York Institute of Technology Dr. Donglin Wang	The ongoing collaboration is related to indoor wireless location and positioning.
Tsinghua University, China Dr. Wenhua Chen	The ongoing collaboration is related to multiband transmitters design and linearization.
Indian Institute of Technologies Dr Mohamad S. Hashmi	The ongoing collaboration is related to waveform engineering in amplifier design.
Aachen University, Germany Dr. R. Negra	The ongoing collaboration is related to the modeling of GaN transistors and the design of switching-mode PAs and transmitters.
Université de Tunis (ENIT, FST, Sup'Com), Tunisia Dr. A. Ghazel (Sup'Com) Dr. A. Gharsallah (FST) Dr. N. Boulejfene (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.
Fraunhofer Institute for Applied Solid State Physics Dr. R. Quay	The ongoing collaboration is related to GaN continuous mode amplifiers.
King Fahd University of Petroleum and Minerals Dr. Mohammad Sharawi	The ongoing collaboration is related to Active Integrated Antenna systems.
American University of Sharjah Dr. Oualid Hammi	The ongoing collaboration is related to linearization of wireless transmitters
Universit of Sharjah, Dr. A. H. Jarndal	The ongoing collaboration is related to modeling of GaN transistors
Ningbo University, China Prof. T. Liu	The ongoing research activities are related to the modeling and compensation of memory effects in RF power amplifiers.
Tsinghua University, Beijing, China Prof. Z. H. Feng	The ongoing research activities are related to the design of dual-band Doherty PAs.
Tampere University of Technology, Tampere, Finland Dr. Mikko Valkama	Collaboration was initiated this year. Ongoing research activities are related to reducing complexity in digital predistortion techniques.
Amirkabir University, Iran Prof. A. Mohammadi	The ongoing research activities are related to six-port receivers and MIMO wireless systems.

7. GRADUATES

Ph.D. Graduates			
Name	Degree	Research Topic	Current Position
Ammar El-Masri	PhD	Green Communication Networks	

MSc. Graduates			
Name	Degree	Research Topic	Current Position
Hosein Taghavi	MSc	Broadband GaN amplifier	
Md Mahmud Hasan	MSc	Adaptive Digital Predistortion	
Dongming (Mike) Wang	MSc	Wireless Channel Modeling	

8. INTELLECTUAL PROPERTY

Patents and Patent Applications

1. F. M. Ghannouchi and M. A. Vejdani, "System and Method For Enhanced Transmitter Efficiency", US Patent Application 1463331375, filed 25 February 2015.
2. F. M. Ghannouchi, S. A. Bassam, M. Helaoui and R. Darraji, "Extended Bandwidth Digital Doherty Transmitter", China Patent Application PCT/CA2013/000678, filed 20 February 2015.
3. F. M. Ghannouchi, S. A. Bassam, M. Helaoui and R. Darraji, "Extended Bandwidth Digital Doherty Transmitter", Swedish Patent Application 1550180-2, filed 18 February 2015.
4. F. Elsayed, M. Helaoui, F. M. Ghannouchi, M. M. Ebrahimi and B. Morris, "Level De-multiplexed Sigma Delta Modulator Based Transmitter", US Patent Application US20150036766 A1, filed 5 February 2015.
5. F. M. Ghannouchi, S. A. Bassam, M. Helaoui and R. Darraji, "Extended Bandwidth Digital Doherty Transmitter", US Patent Application 20150010100 A1, filed 8 January 2015.
6. F. M. Ghannouchi, S. A. Bassam and M. Helaoui, "Multi-Cell Processing Architectures for Modeling and Impairment Compensation in Multi-Input Multi-output Systems," US Patent Application 20140301503 A1, filed 9 October 2014.
7. F. M. Ghannouchi, S. Bensmida, M. Hashmi and M. Helaoui, "Passive source and load-pull architecture for high reflection factor synthesis", US Patent 8,841,922, 23 September 2014.
8. F. M. Ghannouchi and R. Darraji, "Extended Bandwidth Digital Doherty Transmitter", US Patent 8,837,629, 16 September 2014.
9. F. M. Ghannouchi, S. A. Bassam, M. Helaoui and A. Kwan, "Digital multi-band Predistortion Linearizer with Nonlinear Subsampling Algorithm in the Feedback Loop", US Patent 8,817,859, 26 August 2014.
10. F. M. Ghannouchi, M. Helaoui, S. Hatami and R. Negra, "All-Digital Multi-standard Transmitter Architecture using Sigma-Delta Modulators", US Patent Application 20140211886 A1, filed 31 July 2014.
11. S. A. Bassam, F. M. Ghannouchi and M. Helaoui, "Multi-Cell Processing Architectures for Modeling and Impairment Compensation in Multi-Input Multi-output Systems", US Patent 8,767,857, 1 July 2014.
12. M. M. Ebrahimi, M. Helaoui, F. M. Ghannouchi, F. Elsayed and B. Morris, "ACPR Enhanced Complex Delta Sigma Modulator Transmitter", PCT Patent Application PCT/IB2014/062544, filed 23 June 2014.
13. F. M. Ghannouchi, M. Helaoui, S. Hatami and R. Negra, "All-Digital Multi-standard Transmitter Architecture using Sigma-Delta Modulators", US Patent 8,724,733, 13 May 2014.

9. PUBLICATIONS

Refereed Journal Publications

1. H. Taghavi, M. Akbarpour and F. M. Ghannouchi, "Sequential Load-pull Technique for Multi-octave Design of RF Power Amplifiers," IEEE Transactions on Circuits and Systems II: Express Briefs, 2016 accepted.
2. M. S. Sharawi, S. K. Dhar, O. Hammi and F. M. Ghannouchi, "Miniaturized Active Integrated Antennas: A Co-design Approach," IET Microwaves, Antennas & Propagation, 2016 accepted.
3. A. K. Kwan, M. Younes, R. Darraji and F. M. Ghannouchi, "On Track for Efficiency," IEEE Microwave Magazine, 2016 accepted.
4. O. Hammi, M. O. Khalifa, A. Abdelhafiz, A. Kwan, A. Zerguine, M. S. Sharawi and F. M. Ghannouchi, "A Dual-Input Two-Box Model for Digital Predistortion of Envelope Tracking Power Amplifiers," IEEE Microwave and Wireless Component Letters, 2016 accepted.

5. N. Dawar, T. Sharma, R. Darraji and F. M. Ghannouchi, "Linearization of RF Power Amplifiers Exhibiting Memory using Direct Learning based Adaptive Digital Predistoriton," IET Communications, 2016 accepted.
6. R. Darraji, P. Mousavi and F. M. Ghannouchi, "Digitally Enhanced Doherty Power Amplifiers," IEEE Microwave Magazine, 2016 accepted.
7. R. Darraji, M. Honari, R. Mirzavand, F. M. Ghannouchi and P. Mousavi, "Wideband two-section impedance transformer with flat real-to-real impedance matching," IEEE Microwave and Wireless Component Letters, 2016 accepted.
8. N. Chagtmi, N. Boulejfene, R. Darraji and F. M. Ghannouchi, "Synthesis and optimization of new wideband symmetrical six-port junction," IET Microwaves, Antennas & Propagation, 2016 accepted.
9. A. Abdehafiz, L. Behjat, F. M. Ghannouchi and M. Helaoui, "A High-performance Complexity Reduced Behavioral Model and Digital Predistorter for MIMO Transmitters with Crosstalk," IEEE Transactions on Communications, 2016 accepted.
10. S. K. Dhar, M. S. Shawari, O. Hammi and F. M. Ghannouchi, "An Active Integrated Ultra-Wideband MIMO Antenna," IEEE Transactions on Antennas and Propagation, Vol. 64: Issue 4, pp. 1573-1578, April 2016.
11. T. Sharma, R. Darraji, F. M. Ghannouchi and N. Dawar, "Generalized Continuous Class-F Harmonic Tuned Power Amplifiers," IEEE Microwave Wireless and Components Letters, Vol. 26: Issue 3, pp. 213-215, March 2016.
12. O. Hammi, M. H. Khan, A. Abdelhafiz, F. M. Ghannouchi and M. S. Sharawi, "Complexity Reduced Behavioural Modeling of Dynamic Nonlinear Power Amplifiers Using Two-Box Structures," Wiley Microwave and Optical Technology Letters, Vol. 58: Issue 3, pp. 726-731, March 2016.
13. A. E. Abdelrahman, O. Hammi, A. K. Kwan, A. Zerguine and F. M. Ghannouchi, "A Novel Weighted Memory Polynomial for Behavioral Modeling and Digital Predistortion of Nonlinear Wireless Transmitters," IEEE Transactions on Industrial Electronics, Vol. 63: Issue 3, pp. 1745-1753, March 2016.
14. G. Xu, T. Liu, Y. Ye, J. Li and F. M. Ghannouchi, "Generalised two-box cascaded Hammerstein-like digital predistorter for wide-band RF power amplifiers," IET Electronics Letters, Vol. 52: Issue 4, pp. 293-295, February 2016.
15. T. Sharma, R. Darraji and F. M. Ghannouchi, "A Methodology for Implementation of High Efficiency Broadband Power Amplifiers with Second Harmonic Manipulation," IEEE Transactions on Circuits and Systems II: Express Briefs, Vol. 63: Issue 1, January 2016.
16. S. Lajnef, N. Boulejfen, A. Abdelhafiz and F. M. Ghannouchi, "2-D Cartesian Memory Polynomial Model for Nonlinearity and I/Q imperfections Compensation in Concurrent Dual-Band Transmitters," IEEE Transactions on Circuits and Systems II: Express Briefs, Vol. 63: Issue 1, pp. 14-18, January 2016.
17. S. I. Veetil and M. Helaoui, "Discrete Implementation and Linearization of a New Polar Modulator-based Mixerless Wireless Transmitter Suitable for High Reconfigurability," IEEE Transactions on Circuits and Systems I: Regular Papers, Vol. 62: Issue 10, pp. 2504-2511, October 2015.
18. M. Akbarpour, M. Helaoui and F. M. Ghannouchi, "Analytical Design Methodology for Generic Doherty Amplifier Architectures Using Three-Port Input/Output Networks," IEEE Transactions on Microwave Theory and Techniques, Vol. 63: Issue 10, pp. 3242-3253, October 2015.
19. 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, Vol. 9: Issue 3, pp. 664-674, September 2015.
20. M. V. Amiri, S. A. Bassam, M. Helaoui and F. M. Ghannouchi, "Partitioned Distortion Mitigation in LTE Radio Uplink to Enhance Transmitter Efficiency," IEEE Transactions on Microwave Theory and Techniques, Vol. 63: Issue 8, pp. 2661-2671, August 2015.

21. M. V. Amiri, M. Helaoui, N. Boulejfen and F. M. Ghannouchi, "Optimized Spectrum Constrained Crest Factor Reduction Technique Using Polynomials," IEEE Transactions on Communications, Vol. 63: Issue 7, pp. 2555-2564, July 2015.
22. M. S. Hashmi, F. M. Ghannouchi and P. J. Tasker, "High Frequency Waveform Engineering and its Applications: Tutorial 54," IEEE Instrumentation & Measurement Magazine, Vol. 18: Issue 3, pp. 44-50, June 2015.
23. R. Darraji, A. K. Kwan, F. M. Ghannouchi and M. Helaoui, "Digitally Equalized Doherty RF Front-End Architecture for Broadband and Multistandard Wireless Transmitters," IEEE Transactions on Microwave Theory and Techniques, Vol. 63: Issue 6, pp. 1978-1988, June 2015.
24. M. Younes and F. M. Ghannouchi, "Behavioral Modeling of Concurrent Dual-band Transmitters based on Radial-Pruned Volterra Model," IEEE Communication Letters, Vol. 19: Issue 5, pp. 751-754, May 2015.

Refereed Conference Proceedings

1. X. Li, M. Helaoui and F. M. Ghannouchi, "Optimal Fundamental Load Modulation for Harmonically Tuned Switch Mode Power Amplifier," in 2016 IEEE MTT-S International Microwave Symposium (IMS'2016), San Francisco, CA, USA, 22-27 May 2016 accepted.
2. A. K. Kwan, M. Younes, O. Hammi, A. Abdelhafiz, F. M. Ghannouchi and A. O. Fapojuwo, "A Multi-Stage Concurrent Dual-Band DPD Architecture for Closely Spaced Carriers using a Low Bandwidth Feedback Loop," in 2016 IEEE MTT-S International Microwave Symposium (IMS'2016), San Francisco, CA, USA, 22-27 May 2016 accepted.
3. M. Jouzdani, M. Helaoui and F. M. Ghannouchi, "Advanced Envelope Delta-Sigma Transmitter Architecture with PLM Power Amplifier for Multi-Standard Applications," in 2016 IEEE MTT-S International Microwave Symposium (IMS'2016), San Francisco, CA, USA, 22-27 May 2016 accepted.
4. S. K. Dhar, M. S. Shawari and F. M. Ghannouchi, "An Electrically Small Wideband Antenna with Tunable Non-Foster Matching Network," in 10th European Conference on Antennas and Propagation (EuCAP), Davos, Switzerland, 10-15 April 2016 accepted.
5. T. Sharma, R. Darraji and F. M. Ghannouchi, "Design Methodology of High efficiency Contiguous Mode Harmonically Tuned Power Amplifiers," in 2016 IEEE Radio and Wireless Symposium (RWS'2016), Austin, TX, USA, pp. 148-150, 24-27 January 2016.
6. O. Hammi, A. Abdelhafiz, T. Y. Al-Naffouri and F. M. Ghannouchi, "On the Use of Compressed Sampling Algorithms for Impairments Compensation in Dynamic Nonlinear Transmitters," in 15th IEEE International Symposium on Signal Processing and Information Technology (ISSPIT'2015), Abu Dhabi, United Arab Emirates, 7-10 December 2015.
7. S. Lajnef, I. Zemzmi, N. Boulejfen and F. M. Ghannouchi, "2D complexity reduced model for nonlinearity and I/Q imperfections in concurrent dual-band RF transmitters," in 2015 IEEE 15th Mediterranean Microwave Symposium (MMS'2015), Leece, Italy, pp. 1-4, 30 November - 2 December 2015.
8. N. Chagtmi, N. Boulejfen and F. M. Ghannouchi, "Design and implementation of a dual band six-port junction," in 2015 IEEE 15th Mediterranean Microwave Symposium (MMS'2015), Lecce, Italy, pp. 1-4, 30 November - 2 December 2015.
9. F. M. Ghannouchi and A. K. Kwan, "Software Defined Radio Subsampling Receiver for Wireless Monitoring and Sensing Medical Applications," in IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB'2015), Montreal, QC, Canada, pp. 1-5, 4-7 October 2015.
10. F. Ghods, A. O. Fapojuwo and F. M. Ghannouchi, "Energy Efficiency and Spectrum Efficiency in Cooperative Cloud Radio Access Network," in 2015 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM'2015), Victoria, BC, Canada, pp. 280-285, 24-26 August 2015.

11. M. Jouzdani and F. M. Ghannouchi, "High Efficiency Delta-Sigma Transmitter Architecture with Gate Bias Modulation for Wireless Applications," in IEEE 58th International Midwest Symposium on Circuits & Systems (MWSCAS'2015), Fort Collins, CO, USA, pp. 1-4, 2-5 August 2015.
12. S. K. Dhar, M. S. Sharawi and F. M. Ghannouchi, "Port isolation enhancement via active integration for a UWB MIMO antenna system," in 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Vancouver, BC, Canada, pp. 1564-1565, 19-24 July 2015.
13. M. Akbarpour, M. Helaoui and F. M. Ghannouchi, "Efficiency Optimized 60 GHz CMOS Power Amplifier for High PAPR Signals," in 8th Global Symposium on Millimeter-Waves (GSMM'2015), Montreal, QC, Canada, pp. 1-3, 25-27 May 2015.
14. A. Abdelhafiz, O. Hammi and F. M. Ghannouchi, "A Lattice-based Memory Polynomial Behavioral Model for Nonlinear MIMO Transmitters Using Fixed Point Arithmetic," in 2015 IEEE MTT-S International Microwave Symposium (IMS'2015), Phoenix, AZ, USA, pp. 1-4, 17-22 May 2015.
15. A. Ben Arfi, M. Helaoui and F. M. Ghannouchi, "All-digital sigma-delta RF modulator for software defined radio applications," in 2015 IEEE 28th Canadian Conference on Electrical and Computer Engineering (CCECE'2015), Halifax, NS, Canada, pp. 1379-1382, 3-6 May 2015.
16. R. Essaadali, A. Kouki, A. Jarndal and F. M. Ghannouchi, "Modeling of extrinsic parasitic elements of Si based GaN HEMTs using two step de-embedding structures," in 2015 IEEE 16th Annual Wireless and Microwave Technology Conference (WAMICON'2015), Cocoa Beach, FL, USA, pp. 1-4, 13-15 April 2015.
17. S. K. Dhar, O. Hammi, M. S. Sharawi and F. M. Ghannouchi, "Power amplifier based integrated and miniaturized active antenna," in 2015 9th European Conference on Antennas and Propagation (EuCAP'2015), Lisbon, Portugal, pp. 1-4, 13-17 April 2015.

Books and Book Chapters

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

Special/Invited Presentations:

1. Professor F. M. Ghannouchi gave an invited talk entitled "Advanced Power Amplifiers for Broadband Wireless Transmissions" at Dalhousie University, Halifax, Canada, on May 5, 2015.
2. Professor F. M. Ghannouchi gave an invited talk entitled "Energy-Aware Transmitters for Software Defined Radio Applications" at University of Stuttgart, Germany, on April 20, 2015.
3. Professor F. M. Ghannouchi gave an invited talk entitled "Software Defined Radio Subsampling Receiver for Wireless Monitoring and Sensing Medical Applications" at IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB'2015), Montreal, QC, Canada, pp. 1-5, 4-7 October 2015.
4. Professor F. M. Ghannouchi gave an invited talk entitled "Advanced Power Amplifiers and transmitters for SDR applications " at 2016 German Microwave Conference, Bochum, Germany March 15, 2016
5. Professor F. M. Ghannouchi gave an invited talk entitled "Enabling RF technologies for 5G communication Networks" at Qatar University, Doha, Qatar, on April 14, 2016.
6. Professor F. M. Ghannouchi gave an invited talk entitled "RF technologies for 5G communications and IoT Networks" at Microwave and Wireless Technologies Conference, Sharjah, UAE, on April 12, 2016.

Seminars

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

10. OUTREACH

The iRadio Lab continued its support in different science and education outreach efforts over the past year. We strongly believe in propagating the application of RF and microwave technology to the community at large. As a result, the lab founded an IEEE Special group on humanitarian technology (SIGHT) in the year 2015 with an objective to using the low-cost microwave technology in humanitarian activities like disaster readiness, health care and education. The concept of SIGHT propagated and researchers were invited to deliver talks on the application of low-cost microwave technology for humanitarian application in parts of developing world like Sri Lanka, India and Mexico. In continuing to the above, the team from iRadio mentored the undergraduate students at the university and encouraged them to pursue Radio frequency design through Student Teachers and Researchers (STAR) mentorship program. The members are well engaged with the scientific programs at the University of Calgary wherein graduate student lecture, judge different competitions and presentations.

The graduate research members of iRadio Lab started the Amateur HAM Radio group at the University of Calgary to engage the undergraduate, graduate and community members to get trained and licensed on Ham Radio. Two big events in collaboration with IEEE and International Amateur Radio Union (IARU) were hosted in University. The long-term objective of the program is to create a task force of radio operators on campus who can offer help during times of natural or manmade disasters to the city of Calgary and Alberta at large.

11. FINANCIAL REPORTS

AITF Revenues/Expenses

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

Funding Sources

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

- AITF, Alberta Government (ASRA, other)
- University of Calgary (cash)
- University of Calgary (in-kind)
- Industry (cash)
- Industry (in-kind)
- Canada Research Chair
- Canada Foundation for Innovation
- Natural Sciences and Engineering Research Council of Canada
- Other Federal Government
- Other Government