Alberta Informatics Circle of Research Inc.

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) to April 30, 2018.

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 at 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. Additional space in A Block of the Engineering Building (ENA 5 is also being utilised by graduate students, and researchers for printed circuit board fabrication and prototyping) and The Canada Foundation for Innovation (CFI) funded mm-wave facility, has been installed in a newly allocated space (ENA 108). 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, wireless and satellite 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 38 refereed journal papers (published and accepted), 12 refereed conference papers (published and accepted), one US patent application, one US patents and one Canadian patent allowed, and the publication of one book. Four keynote and invited talks were given by iRadio Lab researchers at international conferences and leading research institutions and universities. Two PhD students, Tushar Sharma and Abubaker Abdelhafiz and Mohsin Aziz were awarded AITF-ICT scholarships; and, a fourth PhD student, Sagar Dhar, was the recipient of the Killam scholarship PhD Award. A Fifth PhD student, Xiang Li, was the recipient of an AITF Doctoral Award for Chinese Students. Abdul Rafay is also the recipient of Queen Elizabeth II Scholarship. Two visiting Chinese PhD students, X. Du and W. Zhang, who are financially supported by China Research Council, joined the iRadio Lab for a two-year stay. A PhD student, Mahmood

Noweir, is fully financially supported by a scholarship from Libyan government and a second PhD student, Ahmed Abounemra, is also fully financially supported by a scholarship from Egyptian government. Dr Farid Jolani and Dr. Mohammad Maktoomi were the recipients of the University of Calgary Eyed High Postdoctoral Fellowships.

During its eleventh's year, iRadio Lab was successful in securing funding amounting to $288 K, $200 K and $165 K from NSERC, Canada Research Chairs (CRC) program and the University of Calgary, respectively. Also, 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 $338 K.

2. RESEARCH PROGRAM OVERVIEW

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. Moreover, RF front-ends. This multidisciplinary research calls for broad knowledge in the fields of digital signal processing (DSP), mixed signal electronics and microwave and mm-wave technology and communications systems, including implementation and development of proof-of-concepts and engineering prototypes. The ongoing research activities follow the research directions that were identified in the Chair's renewal proposal and can be categorised in the following major research directions.

Charcterization and Modeling Technology The development of device, circuit, and system models is essential for the design and optimization of the RF front-ends. Equivalent circuit based modeling is needed for circuit level simulation and optimisation. 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 Amplification 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 Impairment's Compensation of RF Front-Ends 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 (SDR) The design of multiband, multimode transmitters is an important element for the development of truly software-defined radio (SDR) based transmitters for the next generation (5G) of wireless 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 Adaptive and reconfigurable receivers are the counterparts of the software-defined-radio (SDR) based transmitters. Both of these components contribute towards the overall system design of high-quality multi-standard and/or multiband transceiver (*trans*mitter + re*ceiver*) systems. New design approaches and system topologies are essential for development and deployment of multi-mode, multi-band communication systems.

Microwave and Millimetre Wave Integrated Circuit Design 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 the battery or as a primary source in self-powered low power radios or sensors applications has drawn significant research attention. In order to increase their operating autonomy and reduce operating costs of sensor networks, 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 thermal energy dissipation within the RF front-end and sensors with the aim to develop power efficient, 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 PROJECT AND ACHIEVEMENTS

The research program is being conducted in those above seven 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.

Charcterization and Modeling Technology

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

Modeling and Linearization of Envelope Tracking Transmitters Envelope tracking (ET) power amplifiers enables high efficient operation at low output back-off power levels, as it adapts the drain voltage of the PA according to the signal envelope characteristics. Using a combination of ET to boost efficiency at low output power regions and digital predistortion (DPD) to compensate for nonlinearity effects have been concurrently used for the design of highly efficient transmitters. A two-box model was proposed which is based on a distributed dynamic nonlinearity approach, which is comprised of a MP and a look-up table (LUT) cascaded together. The benefit of this type of architecture is that the LUT focuses on modeling the nonlinear characteristics, while the MP compensates for any memory effects. For characterization of the LUT, an estimated weighted moving average technique was used to remove the dependency of fitting the nonlinearity

using a mathematical function. The proposed model was able to reduce the spectral regrowth of the ET PA significantly even at the high-power regions.

Linearization of Multi-Band Transmitters Novel transmitter designs allows for the deployment of multiple input transmissions in the RF front end using different hardware topologies. Hence, multi-band architectures with one PA that can operate at different frequency bands are desirable. In this type of architecture, the RF signals are generated using different modulators and then combined using a low- power combiner. Similar to single-band transmitters, multi- band transmitters exhibit inherent distortion; and there is an inverse relation between the efficiency and linearity of the transmitter. A general novel approach for multi-dimensional piecewise modeling was proposed using vector quantization. This method is suitable for the characterization of efficient concurrent dual-band transmitters that exhibit challenging nonlinearity behavior that differ in the low- and high-power regions. In single-band transmitters, the piecewise approaches are based on setting breaking points functions that decompose the input signal into several segments according to a threshold to the input signal amplitude; therefore, independent sub-models are adopted in the different segments. For multi-band transmitters, the PA output is dependent on the envelope of the combined input signals, thus partitioning the model according to the single-input amplitude is not a viable solution. Different combined amplitudes that are constructed based on the input signals' individual amplitudes can be a better solution for segmentation of multi-band transmitters

Modelling and Impairments Compensation in Multi-Port Receivers Modeling and impairments compensation's algorithms for multi-port receivers have been developed which take into account all the known circuit and system non-idealities. Three different calibration methods, such as real-valued, time-delay neural network (RVTDNN), modified memory polynomial (MMP), and modified RVTDNN are proposed to recover the baseband signals from the single-band multi-port receiver, and the dual-band six-port receiver, respectively. For the single-band application, only the non-ideal six-port correlator, the memory effects and the nonlinearity of the diodes are taken into consideration. However, besides the above-mentioned impairments, the in-band nonlinear distortion and inter-band modulation distortion are also taken into consideration during the calibration for the dual-band applications.

Behavioral Modeling of Mixer-less Tranmitters A Triadic Complex Memory Polynomial (TC-MP) based model for forward and inverse modeling of mixerless three-way amplitude modulator based transmitter was proposed. Extensive simulations and measurements have been used to validate the performance of the model. Moreover, the model met the desired design criteria concerning NMSE and adjacent channel leakage ratio (ACLR).

Green Microwave Amplification Technology

The research activities in this track have been supported by NSERC grants, the CRC Chair grant and the AITF Chair grant and Canadian Space Agency.

Broadband Switching-mode PAs The switch-mode PAs like Class F and inverse Class F design were designed to extend their operation at different output power back off levels. The concept of waveform shaping for back–off applications was applied to realize power amplification sub-blocks in load modulation based power amplifiers.. For experimental validation, the implementation was carried out using a 1.95 mm gallium nitride (GaN) die. The single-ended PA is designed to operate as a carrier PA in a 35 dBm average asymmetric Doherty configuration (44 dBm peak power). The PA exhibits a drain efficiency of 78% at an

average output power of 35 dBm at a frequency of 2.6 GHz. The joint collaborative work with NXP Semiconductors is reported at the *International Microwave Symposium 2017*, to be held in Hawaii, June 2017.

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, generalized governing equations for carrier and peaking transistor current ratios, voltage profiles, and biasing conditions are derived in order to assess the performance of any Doherty amplifier configuration. The generalization demonstrates the impact of the selection of the output combiner on PA performance and highlights the trade-offs between the different solutions. To validate the proposed design formulas, a 20-W wideband Doherty PA was designed and tested. Measurements show a good agreement with theory and simulations. The circuit demonstrator maintained more than 40% drain efficiency at 6-dB OPBO over the frequency range of 0.55–1.10 GHz, which covers the commercial GSM, CDMA, and LTE bands. The linearizability of the PA was also successfully verified using 20-MHz LTE signal.

GaN MMIC PAs Recently, the high-efficiency GaN based power amplifiers are highly desired in integrated circuits for wireless and satellite communication systems. Especially for space applications, high power density devices are needed due to the size limitation, while the efficiency is also important for the power dissipation that would make the thermal design difficult. Several C-band and X-band MMIC designs with GaN devices have been designed and shown a good performance and cross a very wide bandwidth. A two-stage configuration is utilized for the design while distributed or lumped matching networks are designed to achieve a high power within the target bandwidth. The simulation shows an output power of 35dBm with 0.5 dB gain flatness is reached within 5% bandwidth for C-band application, while an output power of 37dBm with 1dB gain flatness is reached within 12% bandwidth for X-band application. A peak efficiency of 39% and 42% is approached for C- and X-band, respectively.

DSP for Impairment's Compensation of RF Front-Ends

These following projects have been supported by NSERC grants, the AITF research grant, and the CRC Chair grant

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 hardware impairment and distortions of wireless transceivers in the case of single-input single-output (SISO) and multi input-multi output (MIMO) systems are the object of this project. Indeed, the effects of RF imperfections are more pronounced in MIMO transmitters, whereas many transceivers are mounted on a single-chip and separate communication channels are used for each radio paths. Mitigation algorithms have been developed and validation using 4G long-term evolution (LTE) and 5G filter bank multicarrier (FBMC) signals.

5G Signalling and Evaluation The drastic growth rate in recent usage of smartphones and tablets have led to a dramatic increase in global mobile data traffic. Providing support for high consumer data traffic and maintaining high system efficiency are key requirements of the fifth generation (5G) wireless network design.

In this regard, new waveforms have been proposed as alternatives to the traditional orthogonal frequency division multiplexing (OFDM) to meet the key requirements of the high data rate. Filter bank multicarrier (FBMC) is a foremost candidate waveform for 5G, where using offset quadrature amplitude modulation, along with filter bank, improves data rate. Currently, FBMC waveform, as an emerging technology, requires more in-depth study to understand its capabilities and limitations. This project investigates and experimentally examines FBMC waveform to evaluate its performance while considering different values of the overlapping factor and compares it with OFDM waveform when passed through a realistic nonlinear transmitter. A very nonlinear PA (Doherty) and a moderately linear PA (Class AB) is used to study the behavior of OFDM and FBMC signals regarding the adjacent channel power ratio (ACPR) and the error vector magnitude (EVM). Under the case study, DPD successfully compensates for the PA nonlinearity by boosting both the EVM and ACPR metrics to maintain PA operation at high power efficiency.

PAPR Reduction and Blind Transceiver Impairments Post-Compensation Signals with high Peak-to-Average Power Ratio (PAPR) drives the transmitter 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. An optimization based method for a polynomial based clipping method is proposed to reduce the PAPR, and a post-compensation technique was used to eliminate the resulting nonlinearity. Also, a closed form joint probability density function for PA nonlinearity and I/Q imbalance has been derived and validated. Extensive simulations have been carried out to measure the accuracy of the proposed density function. Using this expression, the effects of I/Q imbalance in the presence of PA nonlinearity can be mitigated at the receiver. Furthermore, a blind estimation method based on power spectral density is proposed to compensate for carrier frequency offset (CFO) in the presence of phase noise (PN) has been tested and found validated using 4G signals.

Software Defined Radio (SDR)

The research activities focusing on the Software Defined Radio (SDR) have been supported by an NSERC strategic grant and AITF funds.

Digitally Assisted and Spurious-free Mixer-less Direct Carrier Modulator Based on the Six-port Modulator A new approach to design a digitally assisted as well as spurious-free direct carrier mixer-less modulator based on the six-port correlator has been proposed. The calibration of the modulator based on modified Cartesian memory polynomial (MCMP) is used to linearize and mitigate hardware impairment of the whole system. The modulation and up conversion are performed by using variable impedance loads controlled by differential in-phase and quadrature baseband voltages with common-mode voltages. The proposed modified Cartesian memory polynomial can compensate for nonlinearity, frequency responses, and residual carrier leakage, cross-talk between the in-phase and the quadrature signals as well as the hardware impairments. The proof-of-concept of the digitally assisted mixer-less modulator is developed, and its performance is assessed at 2.6 GHz with modern communication signals. The error vector magnitudes (EVM) between the input ideal baseband signals and the signals obtained from the up-converted RF signal are all between 2% to 4%.

Delta-sigma Based Transmitter Delay Compensation Technique A digital compensation block for a first order SDR based Delta Sigma Modulator (DSM) was implemented on hardware to cancel out the effect of the delay

introduced by the blocks used. The measured results are in accordance with the predicted simulation results as regards of the adjacent channel power ratio (ACPR) and coding efficiency. The method proposed is simple to implement and recovers the original transfer function of the DSM after being altered by the latency of the blocks requiring some clock cycles in the hardware processing. This method was tested with different latency values and it showed a robust compensation of the delay effect. The linearity is preserved as well as the oversampling speed is kept low.

Hardware Integration of a Complex Delta-sigma Transmitter A multi-level complex delta-sigma modulator (DSM) topology, including an adaptive noise suppression technique, was investigated. The improvement in performance of this architecture in terms of bandwidth, power efficiency and coding efficiency were measured and compared to Cartesian modulators. The complex DSM transmitter was implemented on the BEEcube Platform. The transmitter impairments, IQ imbalance and DC offset were taken into consideration. A separate bit-streams DSM modulated generated by the platform were used to power a back-to-back load modulated amplifier. The full SDR based transmitter was evaluated using an LTE a 3 MHz LTE signal. The average output power of 39dbm, a coding efficiency of 75% was achieved.

Mixer-less Three-way Amplitude Modulator Based Transmitter In this project, a new transmitter architecture which uses three variable gain amplifiers (VGAs) as envelope modulators was proposed. This topology translates the baseband 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 band-pass filter and makes the transmitter design reconfigurable and more integrable. The performance of the SDR based transmitter was successfully tested using LTE signals of different bandwidths, and the signal quality was assessed in terms of normalized mean square error (NMSE).

Adaptive and Reconfigurable Receivers

The activities carried out within this project have been supported by NSERC Discovery grants and AITF Chair program funds.

Passive Mixer Receivers In conventional passive mixer receivers, an array of parallel connected switches in the RF path of the receiver are used to frequency down-convert an incoming RF signal to baseband. Along with signal frequency conversion from RF to baseband, the passive mixer receivers also exhibit an interesting concept of impedance translation of the low-pass baseband impedances to the band-pass impedance at RF signal carrier frequency. This impedance translation concept is very useful in enhancing the frequency selectivity characteristics of the receiver. The frequency down-converted baseband signals are processed further to recover the in-phase (I) and the quadrature-phase (Q) signals of an actual received RF signal. A novel tunable, blocker and clock jitter tolerant, low power, quadrature phase shift frequency selective (QPS-FS) receiver architecture with energy harvesting capability has been proposed. The use of a single local oscillator clock signal with a passive clock division network improves the receiver robustness against clock jitter and reduces the source clock frequency by a factor of N, compared to PM receivers using N switches ($N \geq 4$). The tunable QPS-FS receiver separates the wanted RF band signal from the unwanted blockers/interferers and these undesired signals are reflected by the receiver, collected and could be energy recycled using an auxiliary energy harvesting device.

Ultra-wideband Multi-Port Based Direct Conversion Receivers In this project, multi-port techniques were used to design a five-port and a six-port single-band receiver, as well as a six-port dual-band receiver. For single-band applications, the five-port receiver has only three outputs that utilizes fewer system resources as compared to six-port receivers where four voltage signals are needed to recover the base band signals. Hence, the five-port receiver has lower cost and complexity than the six-port receiver, while the system performance of both the receiver architectures remains almost identical. For the dual-band application, two power dividers/combiners should be used to combine two local oscillator's (LO) signals. Two baseband signals, corresponding to each RF band, can be retrieved at the outputs by using an appropriate calibration method. An ultra-wideband (UWB, 2-18 GHz) prototype development test setup has been developed for implementing the multi-port based direct conversion receivers.

Microwave and Millimetre Wave Integrated Circuit Design

Mm-wave amplifiers 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 sample's device measurement data to be used for GaN transistor model development to be able to design the mm-wave amplifiers and to be submitted afterward for fabrication at Canadian Photonic Fabrication Center (CFPC) in Ottawa. This project is supported by an NSERC Strategic grant and AITF Chair funds.

Optical Fiber Mm-Wave Links This project is being conducted in collaboration with the Institute of Quantum Science and Astronomy at the University of Calgary, and is targeting the development of a relatively cost-effective and radio over fiber (RoF) transmitters for Down-Link links (DL) 5G wireless networks. Utilizing the electro-optic phenomenon of Lithium Niobate (LiNbO3) intensity interferometer allowing to beat two optical carriers to generate modulated mm-wave carrier. A comprehensive analysis and experimental validation of the proposed RoF transmitter were carried out and results demonstrated the feasibility of the proposed transmitter topology for centralized multi- radio access networks (C-RAN). A complete realistic RoF link was modeled taking into account the optical channel impairments, nonlinearity, and frequency response. Algorithms were applied to reduce the impact of these impairments and improve the signal quality at the antenna to reach an EVM value of around 2-3% using near mm-wave LTE signal.

Energy Harvesting and Recycling

Single Band Bi-Directional Synchronous Rectifier: A rectifier design using high-efficiency switch-mode PAs like class F and class F^{-1} has been studied. The ongoing work deals with the modelling and design problems in rectifiers. A new rectifier model has been proposed which was validated by measuring GaN 1.95 mm die. The model has been adopted to design high-efficiency rectifiers, which achieve in practice rectifier efficiency of 75% along with a feedback rectifier efficiency of 82% at a frequency of 700 MHz. This work is supported by NSERC Discovery grants.

4. OBJECTIVES FOR 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 objectives for the next year are divided specific to the research directions, which are briefly listed in the following subsections.

Charcterization and Modeling Technology To increase the spectrum efficiency and channel capacity in wireless transmissions, new wireless communication standards are moving toward massive MIMO radio's architecture adoption 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 modeling and impairment compensation MIMO RF front-ends. Efforts will be dedicated next year to model such systems and propose algorithms to mitigate their impairments.

Green Microwave Amplification Technology New SMPA classes offering higher design flexibility will be investigated and proposed. By tolerating flexible harmonic tuning, these new PAs will allow for the design of significantly wider band power amplifiers compared to the state of the art. While SMPAs offer excellent power efficiency at saturation, this efficiency degrades at lower operating power when using 4G+ and 5G signals with highly varying envelopes. Load modulation techniques will be used together with multi-harmonic tuning in SMPAs in order to maintain the high efficiency in the power back off. The investigation will include architectures such as multi-level pulse load modulation using SMPAs, harmonically tuned Doherty PAs, and harmonically tuned out-phasing transmitters.

DSP for Impairment's Compensation of RF Front-Ends The predistortion of transmitters with drive signals around 500 MHz will be pursued. 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 500 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.

Software-Defined Radio (SDR) Activities related to broadband all-digital architectures transmitters that take advantage of the flexibility of the digital implementation will be proposed and implemented to ensure energy efficiency, flexibility/reconfigurability over a wide frequency band will be pursued next year. 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. In particular, transmitters using mixer-less RFDACs (RF digital-to-analog converters) that are easily reconfigurable for wide frequency ranges, provide better harmonic rejection 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 will be investigated.

Adaptive and Reconfigurable Receivers The performance of adaptive and tuneable receivers in the presence of strong interferences is a serious challenge. Indeed, in order to ensure flexibility, these receivers 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 and presence of blockers. Activities to

enhance the selectivity performance the developed QPS-FS receiver in the presence of strong interference will be carried on. In particular, impedance-mirroring techniques will be investigated. Up scaling the QPS-FS receiver to wireless frequency's range will also be undertaken.

Microwave and Millimetre Wave Integrated Circuit Design 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 to design mm-wave MMIC amplifiers in order to maintain the high efficiency in the power back off. The investigation will include architectures such as harmonic injection tuned amplifiers and continuous mode amplifier topologies or wireless, space and avionics applications.

Energy Harvesting and Recycling Activities for the next year in this area will focus on; (i) the development of a comprehensive and systematic methodology to design RF rectifier; (ii) improvement to the sensor's sensitivity to low input power, to increase the amount of energy harvested over time period; (iii) the development of a dual band rectifier to increase the amount of energy harvested.

5. RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

Team Leader			
Name (full name please)	**Role**	**% of salary support paid by Alberta Innovates Chair Grant**	**Awards/Special Info**
Dr. Fadhel Ghannouchi	Team Leader, Director of iRadio Lab, AITF Strategic Chair in Intelligent RF Radio Technology and Canada Research Chair (Tier 1) in Green radio Systems Research interests are in the areas of modeling of microwave devices and communications systems, design and linearization of RF amplifiers, and SDR radio systems	10%	Professor Ghannouchi was Member of the board of European Research Council for Advanced Grant Program
Faculty Team Members			
Dr. Mohamed Helaoui	AITF associate, assistant professor Research interests are in the areas of RF and wireless communications, signal processing for ultra-wideband receivers	0%	
Dr. Abu Sesay	Professor Research interests include wireless communications	0%	Dr. Sesay is associated with iRadio Lab
Dr. Abraham Fapojuwo	Professor		Dr. Fapojuwo is associated with iRadio Lab

	Research interests include wireless communications	0%	
Dr. L. Belostotski	Associate Professor Research interests include CMOS RFIC transceivers design	0%	Dr. Belostotski is associated with iRadio Lab
Dr. Laleh Behjat	Associate Professor, Research interests include optimization techniques	0%	Dr. Behjat is associated with iRadio Lab
Post-Doctoral Fellows			
Dr. Ramzi Darraji	Wideband Doherty Power Amplifier Design	30%	NSERC Postdoctoral Fellowship
Dr. Mohammadhassan Akbarpour	Digital Pre-Distortion for Concurrent Multiband and Multiple Antenna Transmission	18%	MITACS – Accelerate Graduate Research Internship Program
Dr. Mayada Younes	Behavioral Modeling and Digital Predistortion of Wireless Transmitters	80%	MITACS - Accelerate Graduate Research Internship Program
Dr. Md Ayatullah Maktoomi	Energy Harvesting	10%	Eyes High Postdoctoral Fellow
Dr. Mehrdad Gholami	Power Amplifier Design	100%	Postdoctoral Fellow
Dr. Andrew Kwan	Digital Pre-Distortion for Concurrent Multiband and Multiple Antenna Transmission	100%	Postdoctoral Fellow
Dr. Farid Jolani	Wireless Power Transmission	10%	Eyes High Postdoctoral Fellow, NSERC Postdoctoral Fellowship
Research Assistants			
Suhas Illath Veetil	Research Assistant	100%	
PhD Candidates			
Anis Ben Arfi	Signal processing techniques for broadband radio applications	100%	
Mohsin Aziz	Data-aided and blind compensation of transceiver's impairments using digital signal processing	0%	Scholarship AITF
Fatemeh Ghods	Dynamic Spectrum Allocation Techniques	50%	
Abul Hasan	60 GHz Multi-port Receivers	0%	
Abubakr Hassan Abdelhafiz	Modeling and Digital Predistortion for 5G Transmitters	30%	Scholarship AITF
Ahmed Abounemra	Integrated Transmitter's Design	0%	Scholarship from Egypt
Xiang Li	Multi-Band Power Amplifier Design	0%	Scholarship from China
Ammar Al-Masri	Energy/Quality-of-Experience Trade-off of Power Saving Modes for VOIP Service	0%	
Tushar Sharma	Digital Doherty Transmitters	20%	Multiple Scholarships
Yulong Zhao	Doherty Based MIMO Active Antenna Systems	0%	China Scholarship Council
Mahmood Rajab Noweir	Mm-wave Multi-mode RoF Transmitters	0%	Scholarship from Libya
Sagar Dhar	Active Phased Array Antenna	10%	AITF and Killam Scholarship

Weiwei Zhang	Single- and Dual-Band Multi-Port Transceivers	0%	Scholarship from China Scholarship Council
Xuekun Du	PhD Visiting Student	0%	Scholarship from China Scholarship Council Supervised by Dr. Fadhel Ghannouchi
Dawood Shekari Beyragh	Power Amplifier Design	50%	
MSc Candidates			
Sichong Li	RF Power Harvesting	50%	Supervised by Dr. Rushi Vyas and Dr. Fadhel Ghannouchi
Abul Rafay	FPGA systems for next-generation Communication Systems	0%	NSERC Scholarship Supervised by Dr. Fadhel Ghannouchi
Aparna Bhardwaj	Transmitter's impairments mitigation	100%	Supervised by Dr. Fadhel Ghannouchi
Milad Tajvidi	MIMO Antenna Beam Forming	0%	Supervised by Dr. Mohamed. Helaoui and Dr. Fadhel Ghannouchi
Other Team Members			
Abul Hasan	Lab Manager	0%	
Andrew Kwan	Lab Manager to October 31st , 2016	30%	
Abubaker Abdelhafiz	Lab Manager from November 1st, 2016	30%	AITF scholarship
Chris Simon	Technical support		This is billed hourly as a support expense & paid from AITF account
Caron Currie	Administrative support to Dr. Ghannouchi and the iRadio Lab team	50%	
Visitors			
Samarth Saxena	PhD Visiting Student – IIT Roorkee	100%	Supervised by Dr. Fadhel Ghannouchi
Amir Vaezi	PhD Visiting Student – Amirkabir University	100%	Supervised by Dr. Fadhel Ghannouchi
Antoine Gros	MSc Visiting Student –A, University of Bordeaux	100%	Supervised by Dr. Fadhel Ghannouchi

6. COLLABORATIONS

	Participants	**Nature of Collaboration**
Provincial	N/A	N/A
National	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		
	Zhejiang University, China 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
	University 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 and Dr. W. Chen	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.
Industrial	NXP Semiconductors, Chandler, USA.	High efficiency amplifiers design
Industrial	Nanowave Technologies, Canada	Amplifiers for Avionic's radar applications
Industrial	Ericsson Canada	Mm-wave amplifier Design
Government Agency	Canadian Space Agency	Design of C and X band MMIC GaN amplifiers
Government Agency	National Research Council	GaN transistor Modeling

7. GRADUATES

Post Doctoral Fellows				
Name	Degree	Research Topic	% of salary/stipend support that was paid by Alberta Innovates Chair grant	Current Position

Dr. Ramzi Darraji	PhD/PDF	Wideband Doherty Power Amplifier Design	30%	Working in Industry in Ottawa
Dr. Mohammadhassan Akbarpour	PhD/PDF	Digital Pre-Distortion for Concurrent Multiband and Multiple Antenna Transmission	18%	Working in Industry in Calgary
Dr. Mayada Younes	PhD/PDF	Behavioral Modeling and Digital Predistortion of Wireless Transmitters	80%	PDF at University of Calgary
Dr. Md Ayatullah Maktoomi	PhD/PDF	Energy Harvesting	10%	PDF at University of Calgary
Dr. Mehrdad Gholami	PhD/PDF	Power Amplifier Design	100%	PDF at University of Calgary
Dr. Andrew Kwan	PhD/PDF	Digital Pre-Distortion for Concurrent Multiband and Multiple Antenna Transmission	100%	Consultant in Calgary
Dr. Farid Jolani	PhD/PDF	Wireless Power Transmission	10%	PDF at University of Toronto
PhD Graduates				
Andrew Kwan	PhD	Multi-Band Power Amplifier Design	100%	Consultant in Calgary
Maryam Jouzdani	PhD	Digital Transmitters using Pulse Load Modulation	5%	Senior Engineer at Ciena, Ottawa
Amir Vaezi	PhD	Linearization of MIMO Transmitters (Amirkabir University)	100%	Working as an Engineer in Iran
Afef Hargam	PhD	Behavior modeling of Amplifiers (Al-Manar Tunis University)	0%	Researcher at the University of Tunis
Mohamed A. Al-Masri	PhD	Green Communication Networks	0%	Working as Engineer in Ottawa
MSc Graduates				
Suhas Illath Veetil	MSc	RF Digital to Analog Converters	100%	Working in Industry in Toronto
Aparna Bhardwaj	MSc	Adaptive Transmitter's Impairment Compensation	100%	Working as an Engineer in India
Jatin Chatrath	MSc	Three-way Amplitude Modulator-based Transmitter	0%	Working as Engineer in Vancouver

8. INTELLECTUAL PROPERTY AND COMMERCIALISATION.

Intellectual Property	Status	Application or Patent #	Title	Date	Short Description / Abstract	Jurisdiction
Patents	Applied for this year	20170063316	High Efficiency Ultra-Wideband Amplifier	August 2, 2016	An amplifier comprising an active device having an output terminal for driving a load impedance in response to a signal applied to …	US
	Granted this year	9,461,675	System and method for enhanced transmitter efficiency	October 4, 2016	A method for distortion compensation in a transmission link comprising obtaining information of an amplitude distribution of a signal prior to , …	US
	Granted prior to this year	9,071,496	All-digital multi-standard transmitter architecture using delta-sigma modulators	June 30, 2015	The present disclosure is concerned with a digital transmitter using Delta-Sigma modulators (DMSs) that uses an up-sampler and modulator block that follows the DSMs to generate …	US

		9,071,303	Level de-multiplexed delta sigma modulator based transmitter	June 30, 2015	This specification discloses a level de-multiplexed DSM based transmitter and a method for providing the same. Broadly, embodiments of the present specification enable wireless transmitters that are based on multi-level de-multiplexed DSM….	US
		8,841,922	Passive source and load-pull architecture for high reflection factor synthesis	September 23, 2014	An enhanced loop in a passive tuner consists of an extremely low loss coupler and a high directivity circulator. ….	US
		8,837,629	Extended bandwidth digital Doherty transmitter	September 16, 2014	An extended bandwidth digital Doherty transmitter includes a baseband signal processing block including a digital predistortion unit….	US
		8,817,859	Digital multi-band predistortion linearizer with nonlinear subsampling algorithm in the feedback loop	August 26, 2014	A concurrent multi-band linearized transmitter (CMLT) has a concurrent digital multi-band predistortion block (CDMPB) and a concurrent multi-band transmitter (CMT) connected to the CDMPB….	US
		8,767,857	Multi-cell processing architectures for modeling and impairment compensation in multi-input multi-output systems	July 1, 2014	The present invention relates to a method for multiple-input multiple-output impairment pre-compensation comprising: receiving a multiple-input signal; generating a pre-distorted multiple-input signal from the received multiple-input signal; …	US
		2704522	Multi-cell processing architectures for modeling and impairment compensation in multi-input multi-output systems	February 14, 2017	The present invention relates to a method for multiple-input multiple-output impairment pre-compensation comprising: receiving a multiple-input signal; generating a pre-distorted multiple-input signal from the received multiple-input signal ,…	Canada
Please note: These are 6 of Dr. Ghannouchi's 18 U.S. patents entries on the U.S. Patent and Trademark Office database. For a complete list and description, please visit: USPTO website or click on the hyperlink at the end of each short description.						
University Report of Inventions						
Licenses	New	National Research Council	GaN Transistor Modeling	November 2016	Rights to use the equivalent circuit model of GaN transistor being developed at U of Calgary under NSERC-SPG grant	Canada
		Nanowave Technologies	GaN MMIC Amplifier	December 2016	Rights to use the GaN MIMIC amplifier for space and avionics applications being developed at U of Calgary under NSERC-SPG grant	Canada
		Canadian Space Agency	C and X band MMIC Amplifiers	August 2016	Rights to use the GaN MIMIC amplifier for space and applications being developed at U of Calgary under a PWGSC contract	Canada
	Past	Ericsson Canada	DSM based Transmitters	Mars 2014	Rights to use the DSM based transmitter's architecture for wireless applications developed at U of Calgary under an NSERC-CRD grant	Canada
Spinoff Companies	New	N/A	(Corporate Name and #)			
	Past	N/A	N/A			

9. PUBLICATIONS

Refereed Journal Publications

1. *Mayada Younes, *Andrew Kwan, *Mohammadhassan Akbarpour, Mohamed Helaoui, and Fadhel Ghannouchi, “Two-Dimensional Piecewise Behavioral Model for Highly-Nonlinear Dual-Band Transmitters", IEEE Transactions on Industrial Electronics, accepted April 2017.
2. *W. Zhang, Y. Liu, Y. Wu, *A. Hasan, F. M. Ghannouchi, *Y. Zhao, *X. Du, and W. Chen, “Novel planar compact coupled-line single-ended-to-balanced power divider,” IEEE Trans. Microwave Theory Tech., 2017 accepted.
3. *W. Zhang, Y. Wu, Y. Liu, C. Yu, *A. Hasan, and F. M. Ghannouchi “Planar wideband differential-mode bandpass filter with common-mode noise absorption,” IEEE Microw. Wireless Compon. Lett, 2017 accepted.
4. *F. Ghods, A. Fapojuwo and F. Ghannouchi, "Throughput reliability analysis of cloud-radio access networks," Wiley Wireless Communications and Mobile Computing, Vol. 16: Issue 17, pp. 2824-2838, December 2016.
5. *M. Jouzdani, M. M. Ebrahimi, M. Helaoui and F. M. Ghannouchi, "Complex Delta-Sigma-Based Transmitter with Enhanced Linearity Performance Using Pulsed Load Modulation Power Amplifier," IEEE Transactions on Microwave Theory and Techniques, 2017 accepted.
6. *M. Akbarpour, F. M. Ghannouchi and M. Helaoui, "Current-Biasing of Power-Amplifier Transistors and Its Application for Ultra-Wideband High Efficiency at Power Back-Off," IEEE Transactions on Microwave Theory and Techniques, 2017 accepted.
7. *M. A. Maktoomi; M. S. Hashmi; F. M. Ghannouchi, "A Dual-Band Port-Extended Branch-Line Coupler and Mitigation of the Band-Ratio and Power Division Limitations," in IEEE Transactions on Components, Packaging and Manufacturing Technology
8. *M. A. Maktoomi, *M. Akbarpour, M. S. Hashmi and F. M. Ghannouchi, "On the Dual-Frequency Impedance/Admittance Characteristic of Multi-Section Commensurate Transmission-Line," IEEE Transactions on Circuits and Systems II: Express Briefs, 2016 accepted.
9. *W. Zhang, X. Shen, Y. Wu, Y. Liu, *A. Hasan, F. M. Ghannouchi and *Y. Zhao, "Planar Miniaturized Balanced-to-Single-Ended Power Divider Based on Composite Left- and Right-Handed Transmission Lines," IEEE Microwave and Wireless Component Letters, Vol. 27: Issue 3, pp. 242-244, March 2017.
10. J. Thabet, R. Barrak, A. Ghazel and F. M. Ghannouchi, "Generalized Bandpass Sampling Algorithm for Multiband Wireless Receivers Suitable for SDR Applications," Springer Circuits, Systems, and Signal Processing, Vol. 36: Issue 3, pp. 1099-1114, March 2017.
11. X. Chen, W. Chen, F. Huang, F. M. Ghannouchi, Z. Feng and Y. Liu, "Systematic Crest Factor Reduction and Efficiency Enhancement of Dual-Band Power Amplifier Based Transmitters," IEEE Transactions on Broadcasting, Vol. 63: Issue 1, March 2017.
12. *M. A. Maktoomi, M. S. Hashmi and F. M. Ghannouchi, "Improving Load Range of Dual-Band Impedance Matching Networks using Novel Load-Healing Concept," IEEE Transactions on Circuits and Systems II: Express Briefs, Vol. 64: Issue 2, pp. 126-130, February 2017.
13. *R. Amirpour, *R. Darraji, F. Ghannouchi and R. Quay, "Enhancement of the Broadband Efficiency of a Class-J Power Amplifier With Varactor-based Dynamic Load Modulation," IEEE Microwave and Wireless Component Letters, Vol. 27: Issue 2, pp. 180-182, February 2017.
14. *A. K. Kwan, *M. Younes, O. Hammi, M. Helaoui and F. M. Ghannouchi, "Linearization of a Highly Nonlinear Envelope Tracking Power Amplifier Targeting Maximum Efficiency," IEEE Microwave and Wireless Component Letters, Vol. 27: Issue 1, pp. 82-84, January 2017.
15. *T. Sharma, *R. Darraji, P. Mousavi and F. M. Ghannouchi, "Generalized design of continuous-mode second harmonic tuned amplifiers," Wiley Microwave and Optical Technology Letters, Vol. 58: Issue 12, pp. 2787-2789, December 2016.
16. *F. Ghods, A. Fapojuwo and F. Ghannouchi, "Throughput reliability analysis of cloud-radio access networks," Wiley Wireless Communications and Mobile Computing, Vol. 16: Issue 17, pp. 2824-2838, December 2016.

17. X. Chen, W. Chen, F. M. Ghannouchi, Z. Feng and Y. Liu, "A Broadband Doherty Power Amplifier Based on Continuous-Mode Technology," IEEE Transactions on Microwave Theory and Techniques, Vol. 64: Issue 12, pp. 4505-4517, December 2016.
18. *W. Zhang, *A. Hasan, F. M. Ghannouchi, M. Helaoui, Y. Wu and Y. Li, "Novel Calibration Algorithm of Multiport Wideband Receivers Based on Real-Valued Time-Delay Neural Networks," IEEE Transactions on Microwave Theory and Techniques, Vol. 64: Issue 11, pp. 3540-3548, November 2016.
19. Z. Wang, W. Chen, G. Su, F. M. Ghannouchi, Z. Feng and Y. Liu, "Low Feedback Sampling Rate Digital Predistortion for Wideband Wireless Transmitters," IEEE Transactions on Microwave Theory and Techniques, Vol. 64: Issue 11, pp. 3528-3539, November 2016.
20. *A. Abdelhafiz, *A. Kwan, *M. Younes, O. Hammi, N. Boulejfen and F. M. Ghannouchi, "Augmented Dual-Band Digital Predistorter for Reducing Cross-Band Intermodulation Distortion Using Predictive Injection Technique," IEEE Transactions on Microwave Theory and Techniques, Vol. 64: Issue 11, pp. 3518-3527, November 2016.
21. *A. Vaezi, A. Abdipour, A. Mohammadi and F. M. Ghannouchi, "Analysis of MIMO-OFDM system impaired by nonlinear dual-band power amplifiers," Springer Analog Integrated Circuits and Signal Processing, Vol. 89: Issue 1, pp. 205-212, October 2016.
22. *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, Vol. 63: Issue 9, pp. 818-822, September 2016.
23. *M. A. Maktoomi, *M. Akbarpour, M. S. Hashmi and F. M. Ghannouchi, "A Theorem for Multi-Frequency DC-Feed Network Design," IEEE Microwave and Wireless Components Letters, Vol. 26: Issue 9, pp. 648-650, September 2016.
24. A. Jarndal and F. M. Ghannouchi, "Improved modeling of GaN HEMTs for predicting thermal and trapping-induced-kink effects," Elsevier Solid State Electronics, Vol. 123, pp. 19-25, September 2016.
25. R. Essaadali, A. Jarndal, A. B. Kouki and F. M. Ghannouchi, "A New GaN HEMT Equivalent Circuit Modeling Technique Based on X-Parameters," IEEE Transactions on Microwave Theory and Techniques, Vol. 64: Issue 9, pp. 2758-2777, September 2016.
26. *M. A. Maktoomi, M. S. Hashmi and F. M. Ghannouchi, "Theory and Design of a Novel Wideband DC Isolated Wilkinson Power Divider," IEEE Microwave and Wireless Component Letters, Vol. 26: Issue 8, pp. 586-588, August 2016.
27. S. Bensmida, O. Hammi, *A. Kwan, M. S. Sharawi, K. A. Morris and F. M. Ghannouchi, "Extending the Characterization Bandwidth of Dynamic Nonlinear Transmitters with Application to Digital Predistortion," IEEE Transactions on Microwave Theory and Techniques, Vol. 64: Issue 8, pp. 2640-2651, August 2016.
28. *R. Darraji, P. Mousavi and F. M. Ghannouchi, "Doherty Goes Digital: Digitally Enhanced Doherty Power Amplifiers," IEEE Microwave Magazine, Vol. 17: Issue 8, pp. 41-51, July 2016.
29. N. Chagtmi, N. Boulejfene, *R. Darraji and F. M. Ghannouchi, "Synthesis and optimization of new wideband symmetrical six-port junction," IET Microwaves, Antennas & Propagation, Vol. 10: Issue 10, pp. 1071-1079, July 2016.
30. *W. Zhang, Y. Wu, Y. Liu, F. M. Ghannouchi and *A. Hasan, "A Wideband Balanced-to-Unbalanced Coupled-Line Power Divider," IEEE Microwave and Wireless Component Letters, Vol. 26: Issue 6, pp. 410-412, June 2016.
31. M. S. Sharawi, *S. K. Dhar, O. Hammi and F. M. Ghannouchi, "Miniaturized Active Integrated Antennas: A Co-design Approach," IET Microwaves, Antennas & Propagation, Vol. 10: Issue 8, pp. 871-879, June 2016.
32. *X. Li, M. Helaoui, F. M. Ghannouchi and W. Chen, "A Quad-Band Doherty Power Amplifier Based on T-Section Coupled Lines," IEEE Microwave and Wireless Component Letters, Vol. 26: Issue 6, pp. 437-439, June 2016.
33. *M. A. Maktoomi, M. S. Hashmi and F. M. Ghannouchi, "Systematic Design Technique for Dual-Band Branch-Line Coupler Using T- and Pi-Networks and Their Application in Novel Wideband-Ratio Crossover," IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 6: Issue 5, pp. 784-795, May 2016.
34. *A. K. Kwan, *M. Younes, *R. Darraji and F. M. Ghannouchi, "On Track for Efficiency: Concurrent Multiband Envelope-Tracking Power Amplifiers," IEEE Microwave Magazine, Vol. 17: Issue 5, pp. 46-59, May 2016.
35. 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, Vol. 26: Issue 5, pp. 361-363, May 2016.

36. *N. Dawar, *T. Sharma, *R. Darraji and F. M. Ghannouchi, "Linearization of Radio Frequency Power Amplifiers Exhibiting Memory Effects using Direct Learning based Adaptive Digital Predistoriton," IET Communications, Vol. 10: Issue 8, pp. 950-954, May 2016.
37. *R. Darraji, M. 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, Vol. 26: Issue 5, pp. 313-315, May 2016.
38. *A. Abdelhafiz, 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, May 2016.

Refereed Conference Proceedings

1. *F. Ghods, A. Fapojuwo, F. Ghannouchi, "Energy Efficiency Analysis of a Cloud-Radio Access Network with Distance–Based Power Control," in 2017 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2017), Windsor, ON, Canada, May 2017.
2. *F. Ghods, A. O. Fapojuwo and F. M. Ghannouchi, "Energy Efficiency Analysis of a C-RAN with Distance-Based Power Control," in 2017 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE'2015), Windsor, ON, Canada, May 2017.
3. *S. Lajnef, N. Boulejfen and F. M. Ghannouchi, "Band-limited 2D Cartesian behavioral modeling of concurrent dual-band RF transmitters," in 2016 11th International Design & Test Symposium (IDT'2016), Hammamet, Tunisia, pp. 250-253, 18-20 December 2016.
4. *P. Aflaki, *T. Sharma, M. Helaoui and F. M. Ghannouchi, "Broadband class-E power amplifier with high cold output impedance suitable for load modulated dual branch amplifiers," in IEEE MTT-S Latin America Microwave Conference (LAMC'2016), Puerto Vallarta, Mexico, pp. 1-3, 12-14 December 2016.
5. *A. Abdelhafiz, F. M. Ghannouchi, O. Hammi and A. Zerguine, "Comparative analysis of power amplifiers' polynomial based models identification using RLS algorithm," in 2016 5th International Conference on Electronic Devices, Systems and Applications (ICEDSA'2016), Ras Al Khaimah, UAE, pp. 1-4, 6-8 December 2016.
6. *M. A. Maktoomi, R. Gupta, M. H. Maktoomi, M. S. Hashmi and F. M. Ghannouchi, "A generalized multi-frequency impedance matching technique," in 2016 Mediterranean Microwave Symposium (MMS'2016), Abu Dhabi, UAE, pp. 1-4, 14-16 November 2016.
7. *M. A. Maktoomi, M. H. Maktoomi, A. P. Yadav, M. S. Hashmi and F. M. Ghannouchi, "Dual-frequency admittance property of two sections transmission-line and application," in 2016 IEEE 59th International Midwest Symposium on Circuits and Systems (MWSCAS'2016), Abu Dhabi, UAE, pp. 1-4, 16-19 October 2016.
8. *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, pp. 1-4, 22-27 May 2016.
9. *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, pp. 1-4, 22-27 May 2016.
10. *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, pp. 1-4, 22-27 May 2016.
11. X. Chen, W. Chen, F. M. Ghannouchi and Z. Fe, "A 1.1GHz bandwidth, 46%-62% Efficiency Continuous Mode Doherty Power Amplifier," in 2016 IEEE MTT-S International Microwave Symposium (IMS'2016), San Francisco, CA, USA, pp. 1-4, 22-27 May 2016.
12. *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, pp. 1-4, 10-15 April 2016.

Books and Book Chapters

1. W. Chen, K. Rawat, and F. M. Ghannouchi, Multiband RF Circuits and Techniques for Wireless Transmitters. Springer, 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. The lab demonstrated the state of art research activities through a booth in International microwave symposium hosted in San Francisco in 2016. The lab members were involved in leading various venues at humanitarian front including Makeathons, HAM Radio trainings and student design contents.

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 be 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. Lab members participated in putting up together the amateur radio station on campus in addition to installing antennas and proper grounding. The 100W station was able to work contacts on HF band and connect to local repeater on the VHF band.

11. FINANCIAL REPORTS

11.1 ALBERTA INNOVATES Revenues/Expenses

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

11.2 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