Name:	Fadhel Ghannouchi	Administrative Use Only:	
Institution:	University of Calgary	SHEET #: 30	VOXCO ID: 527
Program:	Strategic Chair		
Grant Title:	AI Strategic Chair in Intelligent RF Radio Technology		
Reporting Period:	2017/2018	**Submission Date:**	15/05/2018

ALBERTA **INNOVATES**

Annual Progress Report Submission

OVERVIEW & GUIDELINES

This report will be used to assess and measure the annual progress achieved by Alberta Innovates funded SRP research projects and Chair programs. The report should be concise, and will be reviewed for progress toward the milestones and deliverables outlined in the research proposal. Certain information shared through this report will be summarized and aggregated to allow for reporting on the outcomes of Alberta Innovates funding.

This annual report must provide information pertaining to the previous fiscal year, for the period: April 1 to March 31.

Notes:

• In accordance with university policy, progress reports should be submitted to Alberta Innovates by the researcher only after it has been reviewed by the university.

• Financial Reporting (Statement of Revenues and Expenses) is also required and comes from the University Research Services Office; however, researchers must sign off on the report before it can be submitted to Alberta Innovates. Please ensure financial reporting sign-off occurs in a timely fashion.

The deadline for submission of this annual report is:

For SRP Grants: the 1st of May.
For Chair Grants: the 15th of May.

Questions regarding report submission can be directed to:

Adam Brown, SRP and Chairs Program Coordinator at

adam.brown@albertainnovates.ca

(780)-450-5560

1. EXECUTIVE SUMMARY

Please provide an overview of the SRP project or Chair program, including a summary of the year's achievements and outcomes. Please use language that is quite readable for government and industry alike, and suitable for public release. Recommended length is 500 words or less.

The Alberta Innovate strategic Chair in Intelligent RF Radio Technology 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 through the research activities that have been conducted over the last decade in the Intelligent Radio Laboratory (iRadio Lab). The research program centred around the development of enabling technologies related to microwave and millimetre-wave (mm-wave) technologies relevant to

5G (5th generation) wireless, satellite and space communications, and Internet of Things (IoT). The thrust of research program encompasses devices, circuits and systems, adaptive digital signal processing, modeling of devices and systems, linearization and equalization concepts, MIMO and Multi-Antenna (MA) transceivers, software-hardware implementation and integration, design and realization of circuits and systems using hybrid and integrated technologies.

The iRadio Lab staffed with more than twenty-five graduate students and researchers. The main space dedicated to iRadio Lab is at the University of Calgary's ICT building (ICT 305 and ICT 318) and used as offices for graduate students and research staff, as well as the research program's main instrumentation, simulation and design areas. Additional spaces in A Block of the Engineering Building (ENA 5 and ENA 108) utilized for printed circuit board fabrication and prototyping and the mm-wave facility composed of state-of-the-art signal generation and analysis equipment and offers the capabilities of ultra-wideband on-wafer measurement capabilities at mm-wave frequencies (up to 67 GHz).

During the last year, efforts were deployed to meet the research objectives planned within the Alberta Innovate Strategic Chair and the strategic grant obtained from the Natural Science and Engineering of Canada (NSERC) to develop linear and efficient transmitters for RF front-ends for 5G and satellite communications. Moreover, an additional team of researchers and graduate student have been dedicated to develop fully integrated C and X band amplifiers fabricated in space qualified Gallium Nitrate (GaN) process for the fourth-generation of Radarsat constellation. This project is sponsored by the Space Technology Development Program (STDP) of the Canadian Space Agency.

The innovative and application-oriented R&D activities being carried out at iRadio Lab in this past year led to the award of 2 patent and filing of 4 patent applications; the publication of 21 refereed journal papers (published and accepted) and 10 refereed conference papers (published and accepted).

Also,

iRadio Lab researchers gave 6 invited talks and contributions to workshops in international conferences and universities along with others outreach activities.

During the last year, iRadio Lab was successful in securing funding amounting to $338 K, $200 K, $300K

and $175 K from NSERC, Canada Research Chairs (CRC) program, Canadian Space Agency and the University of Calgary, respectively. Also, in-kind contributions and equipment donation in the amounts of about $170 K from CMC, and $230 K of in-kind contributions from the University of Calgary were obtained during the reporting period. Furthermore, many students and postdoctoral fellows have were awarded scholarships and fellowships over the last year, totalling an annual of $270 K.

2. ACHIEVEMENTS AND OVERVIEW

This is the core of the report and should address how the research project / program is progressing towards the goals of the initial research proposal. It should include a description of : (i) research activities undertaken, (ii) results achieved, (iii) challenges identified, and (iv) mitigation strategies.

Recommended length is 1,000-2,000 words. Please include at the beginning of your response a short precis or bullet-point list of the most significant achievements and challenges during the reporting period. It is important to describe progress in not too technical terms and for potential public release.

Blind Compensation of Transceiver's Impairments-Post Compensation: Transceivers in communication systems are responsible for transmission and reception of communication signals. However, they present associated impairments, such as PA nonlinearity, In-phase and Quadrature-phase (I/Q) [1], [2] etc. The iRadio lab proposed methods to compensate for the transceiver's impairments. The performance has been further validated using extensive laboratory measurements. An image rejection of greater than 30 dB has been achieved using a 10 KHz 16 QAM signal.

Impairments caused by the power amplifier have also been addressed in addition to the transmitter's I/Q imbalance. A two-step methodology has been developed [2], where the first step requires compensation of power amplifier's amplitude nonlinearity at the receiver using the distribution function of the amplitude of the received signal. The performance of the proposed technique has been validated using extensive simulations and experiments. For a 3 MHz signal, a Normalized Mean Squared Error of around -40 dB, an Adjacent Channel Power Ratio of around -53 dBc and an Error Vector Magnitude of around 1% has been achieved using simulations. Measurement results show an NMSE of -35 dB and EVM of 1.45 %.[1] Aziz, M.; Ghannouchi, F.M.; Helaoui, M. Blind Compensation of I/Q Impairments in Wireless Transceivers. Sensors 2017, 17, 2948. [2] Aziz, M.; Amiri, M. V.; Noweir, M.; Helaoui, M.; Ghannouchi, F.M. Statistics Based Approach for Mitigation of Modulator's Imperfections and Power Amplifier Nonlinearity for Uplink Scenarios. (Manuscript Under Preparation)

Broadband Switching-mode Power Amplifiers (SMPAs): The iRadio Lab's work in this area resulted in the development of new amplifier classes exhibiting higher energy efficiency by utilizing joint designs of input and output harmonics.

The lab's findings introduced two new classes of operation: class GF and class GF-1

in the field of SMPAs. The performance of Class GF-1

is immune to any change in second harmonic impedance at the input of the device thereby offering a design advantage in the selection of second harmonic source impedance. This work provided a very systematic and clear understanding regarding design of input harmonic terminations for GaN PAs. The work is both supported by active load pull measurements and fabrication of chip on board prototypes which demonstrate state of art performance of 83% and 84.5% efficiency. This research led to the development an iterative active load pull techniques to maximize power efficiency while concurrently terminating both source and load harmonics. The research shows a great potential of application in RF base station products for 5G

[1] T. Sharma, P. Aflaki, M. Helaoui and F. Ghannouchi, "Broadband GaN Class-E Power Amplifier for Load Modulated Delta Sigma and 5G Transmitter Applications," IEEE Access, pp. 1-1, 2018 [2] T. Sharma, S. E. R, R. Darraji, D. G. Holmes, J. Staudinger, J. K. Jones and F. M. Ghannouchi, "High-Efficiency Input and Output Harmonically Engineered Power Amplifiers," IEEE Transactions on Microwave Theory and Techniques, pp. 1-13, 2017.

GaN MMIC Amplifiers: To assess the potential and the capability of GaN devices in space applications, several MMIC driver's amplifiers were designed for C-band and X-band applications. A two-stage configuration is utilized for the design of such amplifiers, while distributed or lumped matching networks are used for high power and broadband purposes. The simulation shows an output power of 35 dBm with 0.5 dB gain flatness is reached within 5% bandwidth for C-band application while an output power of 37 dBm with 1 dB gain flatness is obtained within 12% bandwidth for X-band application. A peak efficiency of 39% and 42% is achieved for C- and X-band, respectively. To validate the simulation, two C-band driver amplifiers and two X-band driver amplifiers were fabricated with UMS technology. On-wafer pulsed small signal test of these drivers showed a good agreement with the simulation. The on-wafer pulsed large signal test results showed an output power of 39 dBm with 0.35 dB gain flatness within 150 MHz bandwidth, and an output power of 38 dBm with 0.5 dB gain flatness within 1.2 GHz bandwidth for C-band and X-band drivers, respectively. Besides the driver amplifier, an X-band high power amplifier (HPA) and a C-band high power amplifier are designed aiming a power added efficiency (PAE) of 40%, and an output power of 46 dBm and 45 dBm, respectively. For the X-band HPA, a one-stage topology is utilized to deliver 46 dBm output power and 42% PAE within 600 MHz bandwidth in the simulation. For the C-band HPA, a two-stage topology is utilized to deliver 46 dBm output power and 40% PAE within 300 MHz bandwidth in the simulation.

Modelling and Impairments Compensation in Multi-Port Receivers: Modeling and impairments compensation algorithm has been developed for a concurrent dual-band receiver based on a single multiport correlator circuit that down-converts concurrent dual-band radio frequency (RF) signals to baseband frequencies. The output power, as well as its spectrum analysis, has been carried out, and then a generalized baseband signal recovery theory has been put forward for concurrent dual-band multi-port receiver calibration based on real-valued time-delay neural network (RVTDNN). This technique take into account the system impairments and signal distortions to retrieve the two baseband signals, simultaneously. An implemented dual-band six-port receiver setup operating in 2-18 GHz frequency band has tested under a common modulated signals for which the measured error vector magnitudes (EVMs) between the transmitted and the received signals were all less than 2%.

[1] W. Zhang, A. Hasan, F. M. Ghannouchi, M. Helaoui, X. Li, Y. Wu, L. Meng, and Y. Liu, “Concurrent Dual-Band Receiver Based on the Multi-Port Correlator for Wireless Applications,” IEEE Transactions on Circuits and Systems II: Express Briefs, (accepted for publication).

Digitally Assisted and Spurious-free Mixer-less Direct Carrier Modulator Based on the Six-port Modulator: Six-port based transceivers architectures are low power consuming system design approach for frequency conversion (frequency up-conversion for transmitter and frequency down-conversion for receiver) of communication signals. In six-port modulator, diode-based variable impedance/loads are used to modulate a continuous wave (CW) local oscillator (LO) signal resulting in a mixer-less direct carrier modulator architecture for wireless transmitters. In real systems, the behavior of variable loads implemented using diodes deviate from their expected ideal behavior. A new method to design a digitally assisted and spurious-free direct carrier mixer-less modulator based on the six-port correlator using a modified Cartesian memory polynomial (MCMP) used to linearize and mitigate hardware impairment is proposed. The modulation and the up-conversion are performed by using the variable loads controlled by the differential in-phase and quadrature-phase baseband voltages together with common-mode voltages. The proposed MCMP is able to compensate for nonlinearity, frequency responses, residual carrier leakage, crosstalk between the in-phase and the quadrature-phase data. The proof-of-concept of digitally assisted mixer-less modulator is developed and its performance is assessed at 2.6 GHz with LTE communication signals. The error vector magnitudes between the input ideal baseband signals and the up-converted radio frequency signals are all between 2% and 4%. The residual carrier leakage, which remains present after imperfect suppression through hardware means, degrades the overall system performance and it can be suppressed completely by means of the proposed memory polynomial model.

[1] W. Zhang, A. Hasan, F. M. Ghannouchi, M. Helaoui, Y. Wu, L. Jiao, and Y. Liu, “Homodyne Digitally Assisted and Spurious-Free Mixerless Direct Carrier Modulator With High Carrier Leakage Suppression,” IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 3, pp. 1475-1488, Mar. 2018.

Passive Mixer Receivers: Power consumption, interference tolerance, frequency tunability, and reconfigurability are some of the major concerns for receiver design for future generations of wireless communication networks.

To address these system design issues, a new passive mixer based receiver design approach, called quadrature phase shift frequency selective (QPS-FS) receiver architecture, has been proposed, analyzed, and its advantages and disadvantages compared to a conventional N-path based passive mixer (P-M) receiver architecture. A complete mathematical analysis and an architecture for a generalized N-phase QPS-FS receiver has been proposed that utilizes at least N/2 times lower frequency clock signal compared to a conventional N-path P-M receiver architecture for frequency down-conversion of an RF modulated signal. The proposed QPS-FS receiver utilizes a new RF signal frequency down-conversion and quadrature demodulation approach that reduces the overall power consumption of the complete receiver system, extends the receiver's frequency coverage range, and makes the receiver performance tolerant to clock signals timing jitters.

[1] A. Hasan and M. Helaoui, "Analysis, Calibration, and Performance Evaluation of a Generalized N-phase Quadrature Phase Shift Frequency Selective Receiver," IEEE Access (Under review). [2] A. Hasan, M. Helaoui, and F. M. Ghannouchi, "Agile Blocker and Clock Jitter Tolerant Low-Power Frequency Selective Receiver with Energy Harvesting Capability," Nature: Scientific Reports, vol. 7, no. 1, Aug. 2017.

Ultra-wideband Multi-Port Based Direct Conversion Receivers: Conventional single-band and dual-band six-port receivers employ various quadrature hybrids and power dividers at their core to implement wave-correlator circuit and for other functions. Some lower complexity ultra-wideband multi-port based direct conversion receivers have been proposed to reduce the cost and system design complexity. A five-port based direct conversion receiver for single-band application that requires less complexity, lower system cost, and lower power consumption compared to a conventional six-port based receiver without any compromise in the system performance has been proposed. Similarly, for concurrent dual-band receiver operation, different from the traditional six-port correlator, a new wave correlator circuit, comprising of one power divider and three quadrature couplers, resulting in three inputs and three outputs, has been proposed and provides decreased hardware complexity, smaller circuit size, and lower power consumption for the system. The calibration algorithm based on the RVTDNN was adapted to this new architecture for concurrent dual-band receiver operation. Finally, a concurrent dual-band low intermediate frequency receiver based on the multiport correlator has proposed that uses only one single local oscillator signal to demodulate the dual-band RF signals concurrently, which greatly reduces the receiver complexity. For all the above systems, the system configuration, output power theory, and the signals power spectrum were analyzed in detail, and then appropriate baseband signal recovery theory has put forward for each of these architectures. All the three new proposed receiver systems provide similar performance as their conventional multi-port based system counterpart but with reduced complexity, smaller size, and lower power consumption.

[1] W. Zhang, A. Hasan, F. M. Ghannouchi, M. Helaoui, C. Yu, and Y. Liu, "Concurrent Dual-Band Low Intermediate Frequency Receiver Based on the Multiport Correlator and Single Local Oscillator," IEEE Microwave and Wireless Components Letters, vol. 28, no. 4, pp. 353-355, Apr. 2018. [2] W. Zhang, A. Hasan, F. M. Ghannouchi, M. Helaoui, Y. Wu and Y. Liu, "Concurrent Dual-Band Receiver Based on Novel Six-Port Correlator for Wireless Applications," IEEE Access, vol. 5, pp. 25826-25834, Oct. 2017. [3] W. Zhang, A. Hasan, F. M. Ghannouchi, M. Helaoui, Y. Wu, and Y. Liu, "Design and Calibration of Wideband Multiport Homodyne Wireless Receivers," IEEE Transactions on Instrumentation and Measurement, vol. 66, no. 12, pp. 3160-3169, Sep. 2017.Receivers with Energy Harvesting and Recycling: For future generations of wireless communication networks, many multi-billion devices are expected to be connected to the internet wirelessly.

Two major concerns faced by the receivers and sensors

designers are the (i) challenges of interferers and blocker signals as the number of radio frequency (RF) radiating devices in the vicinity will increase, and (ii) the challenge of sustainable power consumption and practical limitation of periodic battery charging using wired connection involving human intervention for such a large number of devices in the network. Frequency selective receiver design, and energy harvesting using random RF signals and dedicated wireless transmitters in the network have been suggested as possible solution to address these system design challenges. A new frequency selective and energy harvesting enabled receiver that concurrently receives information data from in-band RF signal and harvests energy from the in- and out-band-band RF signals has been proposed and implemented operating in the frequency band from 100 MHz to 1 GHz. For a receiver with 500 MHz bandwidth, the energy harvester could harvest up to 46.5% of the total LO power consumption of the receiver in a concurrent operation mode (as an information receiver and an energy harvester) while achieving an error vector magnitude (EVM) of 4% with an RF signal power of -25 dBm and blocker signal situated 50 MHz away from the LO frequency having 5 dBm power.

Energy Harvesting: In this work, we presented a synthesis technique for dual-frequency rectifier for ambient RF energy harvesting. For the first time, a fully distributed version of dual-frequency resistance compression network (RCN) is introduced. The proposed RCN utilizes the dual-frequency characteristic of the c-type coupled lines terminated into real impedance. The design technique is fully analytical based on closed-form design equations. Extensive simulations were carried out to illustrate the proposed concept. The obtained results outperform the earlier reported lumped element network and provides a minimum 10% improvement in the RF-to-DC conversion efficiency at –20 dBm input power. The proposed technique can potentially serve as a starting point for the dual-frequency RF rectifier design.

[1] A. Hasan and M. Helaoui, “Towards Self-Powered Receivers for IoT Applications – A New RF Front-end Harvesting the Energy of Interferers,” IEEE Transactions on Industrial Electronics (Under review).

[2] A. Hasan, M. Helaoui, and F. M. Ghannouchi, “Agile Blocker and Clock Jitter Tolerant Low-Power Frequency Selective Receiver with Energy Harvesting Capability,” Nature: Scientific Reports, vol. 7, no. 1, Aug. 2017. [3] M. A. Maktoomi, F. M. Ghannouchi and R. Vyas, "Novel Synthesis of Dual-Frequency RF Energy-Harvesting Rectifier Incorporating Coupled Lines," 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), Toronto, ON, 2017, pp. 1-4.

Radio over Fiber Transmitter: The Radio over Fiber (RoF) and mm-wave project aims at the development of RoF transmitter for front-haul downlink communication link suitable for the next generation (5G) wireless communication. The proposed architecture links one central baseband unit (BBU) to a remote radio head (RRH) unit located about 12 Km away. The downlink is carrying LTE-advanced signals of up to 100 MHz bandwidth (BW) and modulation schemes of up to 256 quadrature amplitude modulation (QAM). Effective hardware impairment mitigation approaches were studied, implemented and experimentally validated to reduce error vector magnitude to 2% and 3.5% for 20 MHz and 100 MHz signals, respectively. Currently, we are conducting several experiments towards improving the link spectral efficiency and capacity to reach 2 Gbps speed.

Appropriate linearization techniques are adapted and scaled from electrical domain to the optical domain to mitigate the inherited distortion due to BW expansion. These models will provide advantages in downsizing and reducing the cost of RoF transceiver’s design.

[1] M. Noweir, Q. Zhou, A. Kwan, R. Valivarthi, M. Helaoui, W. Tittel and F. M. Ghannouchi, "Digitally Linearized Radio-Over Fiber Transmitter Architecture for Cloud Radio Access Network's Downlink," IEEE Transactions on Microwave Theory and Techniques, pp. 1-11, 2018.

Sigma-delta Modulators: The Delta-Sigma Modulator (DSM) are commonly used in radio frequency (RF) receivers as an analogue to digital converter, transforming continuous signals into a high-rate of bi-level pulses they are also used as modulators in digital transceivers. Implementing the DSM processing blocks on a Digital Signal Processor (DSP) or Field Programmable Gate Array (FPGA) is challenging due to the additional tap delays also known as latency required by the processing blocks to calculate and output the result. These inherent tap-delays are required for the Digital Signal Processor (DSP) or Field Programmable Gate Array (FPGA) implementation to allow the gates to process the data at the clock rate. These latencies impact the transfer function of the DSM as these additional tap delays deteriorate the conventional transfer function of DSM, in particular, the noise shaping function known as the Noise Transfer Function (NTF) of the DSM.

A compensation block to cancel out the effect of the undesired tap delays for the Continuous-Time Delta-Sigma modulator (CT-DSM) building blocks is developed and validated. By implementing the augmented transfer functions, we could re-establish the correct and anticipated transfer function response of the DSM

by multiplying with the combination of delays which is equivalent to adding a post-compensation block.[1] A.B. Arfi, F. Elsayed, P. M. Aflaki, B. Morris and F. M. Ghannouchi, "Three-Level De-Multiplexed Dual-Branch Complex

Delta-Sigma Transmitter," Sensors (Basel), Vol. 18: Issue 2, Feb 20 2018.

Linearization of Multi-band Transmitters: Over the past year, the iRadio Lab has continued conducting research in this area; with an emphasis of reducing the observation and sampling rate requirements of wireless systems. A technique based on generating a narrowband static predistorter for the power amplifier was developed. Then, the intended multi-band signals are re-sampled and shifted into their representative carrier frequencies before applying the static predistorter to generate the out-of-phase intermodulation distortion products to compensate for those produced by the nonlinearity. Results presented for the proposed predistorter for two amplifiers: one in a tri-band carrier aggregated LTE scenario in the sub 3 GHz frequencies and another in the 30 GHz band, demonstrating the effectiveness of reducing the intermodulation products using 5G signals. In another work, a two-dimensional piecewise model was developed for highly nonlinear dual-band transmitters. The proposed model is partitioned according to different functions of composite multi-input amplitudes rather than the single input amplitude This model was shown to out-perform all existing models in the literature, and addressed the issue of strong nonlinearities in multi-band systems. In a third work, the complexity of multi-band DPD targeting second harmonics was reduced.

[1] A. K. Kwan, M. F. Younes, O. Hammi, M. Helaoui, N. Boulejfen, and F. M. Ghannouchi, "Selective Intermodulation Compensation in a Multi-Stage Digital Predistorter for Nonlinear Multi-Band Power Amplifiers", IEEE Journal on Emerging and Selected Topics in Circuits and Systems, Vol. 7: Issue 4, pp. 534-546, December 2017. [2] M. Younes, A. Kwan, M. Akbarpour, M. Helaoui and F. M. Ghannouchi, "Two-Dimensional Piecewise Behavioral Model for Highly Nonlinear Dual-Band Transmitters," IEEE Transactions on Industrial Electronics, Vol. 64: Issue 11, pp. 8666-8675, 2017. [3] P. Jaraut, M. Rawat and F. Ghannouchi, "2-D Curtailed Harmonic Memory Polynomial for reduced complexity in Concurrent Dual-Band Modeling and Digital Predistortion with the second band at Harmonic Frequency," IET Communications, 2018.

Continuous-mode Power Amplifiers: Wideband power amplifiers (PAs) with high efficiency at an extensive dynamic range of output power have gained growing attention due to the urgent demand that high peak-to-average power ratio signal requires PAs to operate at large output power back off (OPBO) with high PAE. Various efficiency enhancement techniques have been employed to meet this requirement, such as Doherty and dynamic load modulation (DLM). DLM PAs use a varactor-based matching network to modulate the load impedance of PAs and maintain instantaneous high PAE. The proposed methodology is developed by combining “continuous mode” concept with LM technique, and is validated using a 10-Watts gallium–nitride transistor. The work is reported in IEEE Microwave and Wireless Components Letters and IEEE Asia Pacific Microwave Conference. Then, the design space of load modulated Class-B/J PAs is improved by including the knee voltage effects and soft turn-on characteristic. This work is reported in IEEE MTT-S International Wireless Symposium. Meanwhile, to develop wideband high-linearity PA, an analytical method is proposed to reduce the memory effects and third-order inter-modulation distortions (IMD3). An improved wideband Chebyshev low-pass matching network including the bias network is analyzed and designed to validate the proposed method. This work is reported in International Journal of Microwave and Wireless Technologies.

[1] Xuekun Du, Chang Jiang You, Jingye Cai, Mohamed Helaoui, Fadhel M. Ghannouchi, Yulong Zhao, Xiang Li, “Novel Design Space of Load Modulated Continuous Class-B/J Power Amplifier,” IEEE Microwave and Wireless Components Letters, vol. 28, no. 2, pp. 156-158, Feb. 2018. DOI: 10.1109/LMWC.2017.2779883 [2] Xuekun Du, Chang Jiang You, Sagar K. Dhar, Xiang Li, Mehamed Helaoui, Jiangye Cai, Fadhel M. Ghannouchi, “Analysis on the intrinsic design space of DLM continuous class-B/J power amplifier,” in proceeding of IEEE Asia Pacific Microwave Conference, 2017. DOI: 10.1109/APMC.2017.8251518 [3] Xuekun Du, Chang Jiang You, Xiang Li, Mohamed Helaoui, Jiangye Cai, Fadhel M. Ghannouchi, “Evaluation of Knee Voltage Effect and Soft Turn-on Characteristic on the Load Modulated Continuous Class-B/J Power Amplifier,” in proceeding of IEEE MTT-S International Wireless Symposium, accepted, May 6-10, 2018. [4] Xuekun Du, Chang Jiang You, Yulong Zhao, Xiang Li, Mohamed Helaoui, Jingye Cai, Fadhel M. Ghannouchi, “Wideband high-efficiency linearized PA design

4. PLANS, OBJECTIVES AND MAJOR CHANGES FOR NEXT YEAR

In this section please describe your plans, project / program evolution and proposed work for the next year.

Be sure to include any major changes proposed to the direction of the project or program as it was laid out in the research proposal. Examples include the following: a greater than 20% variation above or below budgeted line items, a significant change in research direction, or a change in expected completion date.

This section has a direct bearing on the report approval process, therefore please be as clear as possible about the general areas of proposed work. Technical details are not required and recommended length is no more than 1,000 words.

1. Development of a nonlinear transistor model for GaN NRC fabrication process

The National Research Council (NRC) of Canada has the only Gallium Nitride (GaN) foundry in Canada,. The iRadio Lab aims to use our established technical know-how in transistor modeling to develop nonlinear transistor models for the NRC GaN fabrication process, with the goal of furthering Canada's technological leadership in this area, and pushing the implementation of GaN technologies in 5G further.

2. Design and prototyping of C and X-band GaN MMIC amplifiers for space applications. While power efficiency is a key metric for power amplifiers, it has an increased importance for space applications; where high power density devices are needed due to size limitations and thermal design considerations are key. Gallium Nitride (GaN) devices have been found to be a good option for high power Monolithic microwave integrated circuit (MMIC) design. Several C-band and X-band MMIC designs with GaN devices have shown good performance across a very wide bandwidth. The iRadio Lab has previously designed several MMIC driver amplifiers for C-band and X-band applications utilizing two-stage configurations, with promising results (efficiencies of 39% and 42% for C- and X-band, respectively). This work will be continued by the lab, with the aim of further improving the performance for C- and X-band for space applications.3. Design and prototyping of K and Ka-band GaN MMIC amplifiers for mm-wave 5G applications.The move to 5G systems requires the use spectral bands that have not been actively utilized to date, such as the K- and Ka- bands. To date, the majority of high power amplifier design is conducted for lower frequency ranges (mainly between 2 and 4 GHz). As a result, it is not possible to scale the low-frequency design methodology up to 5G and mm-wave applications.

Therefore, new design approaches need to be developed. The iRadio lab aims to build on existing knowledge and technologies to produce energy-efficient integrated power amplifiers based on Gallium Nitride (GaN) monolithic microwave integrated circuit (MMIC) for 5G applications.4. Development of a power efficient DSM based transmitter architecture. The Delta-Sigma Modulator (DSM) are commonly used in radio frequency (RF) receivers as an analogue to digital converter, transforming continuous signals into a high-rate of bi-level pulses.

They have been used as modulators in digital transceivers. To date, the iRadio Lab has done extensive work in developing and implementing fast, high-performance DSM systems.

The main goal for the next year is to address the energy efficiency of such systems.5. Development of digital predistortion techniques for the multiband transmitters. 5G systems demand a substantial increase in bandwidth and are projected to use multi-band systems to service more users and increase significantly the data rate of communication links`. The development of multi-band DPDs which can keep up with the explosive increase in signal bandwidth and stronger intermodulation distortions will be needed and lower the observation bandwidths and sampling rates used in the feedback loop. The iRadio Lab has been a very active player in multi-band DPD from developing the core concepts, to developing leading technologies in the area. Going forward, we will be developing multi-stage and bandwidth-reduced multi-band predistortion and intermodulation cancellation techniques, to meet the demands of the 5G standard.

6. Development of a broadband rectifier for energy harvesting purposes. Development of broadband rectifiers for energy harvesting purposes is an essential step towards achieving self-powered and self-sustainable energy-harvesting radio receivers design for future generations sensors networks.

Not only data/information but also the power/energy to the sensor nodes in the network will be sent over the radio frequency signals. Development of broadband energy harvesting circuits will enable the harvesting of larger amount of power from various random interferers and blocker signals in a wide frequency bandwidth with increased power conversion efficiency from radio frequency to direct current (DC).

7. Development of distortion and hardware impairments mitigation

techniques for massive MIMO Radios A primary element of the move from 4G to 5G and beyond is the adoption of large-scale massive MIMO system. In contrast to current 4G systems limited to 2x2 MIMO configurations, 5G demands MIMO systems at least 16x16 in size, going up to 256x256 MIMO radio topology. However, MIMO DPD theory and practice remains largely constrained to the realm of 2x2 MIMO and assumes that the hardware impairments are limited in effect. However this is not the case for 5G, and as such, the iRadio Lab will continue working on the development scalable MIMO DPD models suitable for large-scale MIMO systems.

8. Development of mixers-less receivers for wireless communications

Low-power circuits and systems design helps in achieving increased battery-life and longer maintenance-free operation of nodes in a wireless communication networks and sensors networks. Development of mixer-less receivers for wireless communications and sensor networks to achieve low-power sensor/receiver design is an important target for green and sustainable power consumption as number of wireless communication devices are expected to grow up to 200 billion according to various estimates. iRadio lab will continue working in this area to develop ultra-low power or/ and self-powered sensors/receivers9. Development of Radio-over-fiber (RoF) transmitter for wireless communications networks Radio-over-Fiber (RoF) technologies will play a key role in 5G networks; as they form the backbone of the network between the pico-cells and the centralized processing units, making the transmission of high data rates (~10 Gbps) possible in 5G mmWave systems. Despite their many attractive properties, the optical modulators that are used in this link generate nonlinearity distortion and thus, compensation methods are needed. Building on the iRadio Lab’s legacy in predistortion (DPD) methods, advanced wide-band DPDs suitable for 5G RoF systems will be developed.

5. COLLABORATIONS

Joint work with other universities, research institutes and industry are all valued by Alberta Innovates.

Points to note:

- Include active Bi-lateral or multi-lateral partnerships that have resulted from or are directly linked to this grant

- Include agreement between a member of the research team/group to participate in a network consortium multi-centre study or other initiative

- Under 'Potential Collaborations' include collaboration or partnerships at an early stage of discussion where there has been no tangible output

DO NOT report here:

- Collaborations or partnerships restricted by contractual confidentiality

- Funding gained through successful collaborative funding applications should be reported in answer to question 11, "Other funding" of this report

Alberta Government	0
Other Provincial/Municipal Government	0
Federal Government	2
Academic (Canadian)	3
Academic (International)	14
Industry (Canadian)	1
Industry (International)	1
Not-for-Profit Organization	0
Consortium	0
Potential Partnership	0

Please provide specific details below:

Type of Entity	Name of Entity	Nature of Collaboration	Description
1. Academic (Canadian)	Dr. K. Wu	Applied Research	Poly-Grames Research Center
2. Academic (Canadian)	Dr. C. Akyel	Applied Research	Poly-Grames Research Center
3. Academic (Canadian)	Dr. A Kouki	Academic Collaboration	LINC based amplifiers and GaN transistor modeling
4. Academic (International)	Dr. Donglin Wang	Academic Collaboration	Indoor wireless location and positioning
5. Academic (International)	Dr. Wenhua Chen	Academic Collaboration	Multiband transmitters design and linearization

6. Academic (International)	Dr. Mohamad Hashmi	Academic Collaboration	Waveform engineering amplifier design
7. Academic (International)	Dr. Renato Negra	Academic Collaboration	Modeling of GaN transistors and design of witiching-mode PAs and transmitters
8. Academic (International)	Dr. A. Ghazel	Academic Collaboration	Behaviour Modeling of nonlinear systems
9. Academic (International)	Dr. A. Gharsallah	Academic Collaboration	Implementation of DPD/FPGA modules
10. Academic (International)	Dr. N. Boulejfene	Academic Collaboration	Design of multistandard receivers using RF subsampling techniques
11. Industry (International)	NXP Semicondutors	Applied Research	High efficiency amplifier design
12. Industry (Canadian)	Nanowave Technologies	Applied Research	Amplifiers for Avionic's radar applications
13. Federal Government	Canada Space Agency	Applied Research	Design of C and X band MMIC GaN amplifiers
14. Federal Government	National Research Council	Applied Research	GaN transistor Modeling
15. Academic (International)	Dr. Meenakshi Rawat	Academic Collaboration	Distortion & Impairment Mitigation in SDR Transceivers
16. Academic (International)	Dr. Mohammad Sharawi	Academic Collaboration	Active Integrated Antenna systems
17. Academic (International)	Dr. Oualid Hammi	Academic Collaboration	Linearization of Wireless Transmitters
18. Academic (International)	Dr. Anwar Jarndal	Academic Collaboration	Modeling of GaN Transistors
19. Academic (International)	Prof. T. Liu	Academic Collaboration	Modeling and Compensation of Memory Effects in RF Power

			Amplifiers
20. Academic (International)	Prof. Z.H.Feng	Academic Collaboration	Design of Dual-Band Doherty PAs
21. Academic (International)	Prof. A. Mohammadi	Academic Collaboration	Six-port Receiverrs and MIMO Wireless Systems

6. RESEARCH TEAM MEMBERS

Within the research team, please provide the number of people in each of the categories below:

Team Leader	1
Faculty Team Member	5
Research Staff	4
PhD Candidate	12
MSc Candidate	1
Visitor	3
Undergraduate	0
Support Staff	2

*Research Staff includes: Post-Doctoral Fellows, Research Engineers, Research Associates, etc.

Please indicate the total number of full-time equivalent (FTE) positions across all of the above categories that were directly supported using Program Funds in this reporting period
(ex. if MSc candidate student 25% supported by Program Funds, that is 0.25 FTE Position):

4.55

Since your program involves a variety of partners, it is important to identify their roles in the program. In the table below, please provide the role, full name, e-mail and any awards or special information that should be noted.

Role	Name	Email	Awards/Special Info
1. Team Leader	Fadhel Ghannouchi	fghannou@ucalgary.ca	Chair and Lab Director
2. Faculty Team Member	Mohamed Helaoui	sesay@ucalgary.ca	Associate Professor , Associated with the Chair
3. Faculty Team Member	Abu Sesay	lbelosto@ucalgary.ca	Professor, collaborating with Chair
4. Faculty Team Member	Abraham Fapojuwo	No longer available	Professor, collaborating with the Chair
5. Faculty Team Member	Leonid Belostotski	mehrdad.gholami@ucalgary.ca	Professor, Collaborating with the Chair

6. Faculty Team Member	Laleh Behjat	abenarfi@ucalgary.ca	Professor, collaborating with the Chair
7. Research Staff*	Mayada Younes	ahasan@ucalgary.ca	Postdoctoral Researcher
8. Research Staff*	Md Ayatullah Maktoomi	ahmed.abounemra@ucalgary.ca	Postdoctoral Researcher, NSERC and Eyes High awards
9. Research Staff*	Mehrdad Gholami	yulong.zhao@ucalgary.ca	Postdoctoral Researcher
10. Research Staff*	Hwiseob Lee	sagar.dhar@ucalgary.ca	Postdoctoral Researcher
11. PhD Candidate	Anis Ben Arfi	duxuekun@163.com	PhD Candidate
12. PhD Candidate	Mohsin Aziz	rafay.aslamkhan@gmail.com	PhD Candidate, Eyes High scholarship, Calgary Innovates award
13. PhD Candidate	Abul Hasan	fghods@ucalgary.ca	PhD Candidate, University of Calgary Productivity Award
14. PhD Candidate	Abubakr Hassan Abdelhafiz	caron.currie@ucalgary.ca	PhD Candidate, Eyes High Scholarship, Schulich School of Engineering award, Lab manager
15. PhD Candidate	Ahmed Abounemra		PhD Candidate, Scholarship from Egypt military and government
16. PhD Candidate	Tushar Sharma		PhD Candidate, Killam scholarship, Astech Future Leader Award, Industry internship
17. PhD Candidate	Yulong Zhao		PhD Candidate, China Scholarship Council scholarship
18. PhD Candidate	Mahmood Noweir		PhD Candidate, Scholarship from Libyan Governement
19. PhD Candidate	Sagar Dhar		PhD Candidate, Killam Scholarship

20. Visitor	Weiwei Zhang	Visitor PhD Candidate, China Scholarship Council
21. Visitor	Xuekun Du	Visitor PhD Candidate, China Scholarship Council
22. PhD Candidate	Dawood Shekari Beyragh	PhD Candidate
23. MSc Candidate	Abul Rafay	NSERC award
24. Visitor	Praveen Jaraut	Visitor PhD Candidate, Indian Institute of Technology , Roorkee
25. PhD Candidate	Fatemeh Ghods	Co-Supervised by Dr Fapojuwo and Dr Ghannouchi
26. PhD Candidate	Xiang Li	PhD Candidate
27. Support Staff	Caron Currie	Admin Support
28. Support Staff	Christopher Simon	Tech Support

7. GRADUATES & COMPLETED POST-DOCS

Alberta Innovates is committed to increasing the number of graduates in areas of strategic importance to Alberta. Please provide information on last year's graduates using the tables below:

Post-Doctoral Fellow	1
PhD Graduate	2
MSc Graduate	0

Please indicate the total number of full-time equivalent (FTE) positions across all of the above categories that were directly supported using Program Funds in this reporting period
(ex. if MSc candidate student 25% supported by Program Funds, that is 0.25 FTE Position):

0.5

Please provide specific information on graduates below:

Role	Name	Email	Awards/Special Info
1. PhD Graduate	Fatemeh Ghods	fghods@ucalgary.ca	University of Calgary Productivity Award
2. Post-Doctoral Fellow	Mayada Younes	mfyounes@ucalgary.ca	
3. PhD Graduate	Xiang Li	lxiang@ucalgary.ca	

8. INTELLECTUAL PROPERTY

Using the tables below, please provide information pertaining to intellectual property.

In the table immediately below, use the second column (# Granted in the Year) for reporting spin-off companies:

	# Applied in the Year	# Granted in the Year
Patents	4	2
Licenses	0	0
Spin-Offs	1	0
Other	0	0

*For Spin-Offs, please list Corporate Name / # in Title Column.

Date: 17/05/2017 **Status:** Granted
IP Type: Patents **#:** 9,641,204 **Jurisdiction:** USA

Title: Digital multi-band predistortion linearizer with nonlinear subsampling algorithm in the feedback loop

Description: 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. The CDMPB can have a plurality of digital baseband signal predistorter blocks (DBSPBs), an analyzing and modeling (A&M) stage, and a signal observation feedback loop. Each DBSPB can have a plurality of inputs, each corresponding to a single frequency band of the multi-band input signal, and its output corresponding to a single frequency band; each output connect corresponding to an input of the CMLT. The A&M stage can have a plurality of outputs connected to and updating the parameters of the DBSPBs, and a plurality of inputs connected to either both outputs of the signal observation loop or the output of the subsampling loop and to outputs of the DBSPBs. The A&M stage can perform signals' time alignment, reconstruction of signals and compute parameters of DBSPBs.

Date: 11/04/2017 **Status:** Granted
IP Type: Patents **#:** 9,621,236 **Jurisdiction:** USA

Title: System and method for distortion correction in MIMO and multiband transmitters

Description: 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; generating a multiple-output signal by feeding the pre-distorted multiple-input signal into a multiple-input and multiple-output transmitter; estimating impairments generated by the multiple-input and multiple-output transmitter; and adjusting the pre-distorted multiple-input signal to compensate for the estimated impairments. The present invention also relates to a pre-compensator for use with a multiple-input and multiple-output transmitter, comprising: a multiple-input for receiving a multiple-input signal; a matrix of pre-processing cells for generating a pre-distorted multiple-input signal from the received multiple-input signal; and a multiple-output for feeding the pre-distorted multiple-input signal to the multiple-input and multiple-output transmitter. The pre-processing cells are configured so as to estimate impairments generated by the multiple-input and multiple-output transmitter and adjust the pre-distorted multiple-input signal to compensate for the estimated impairments.

Date: 22/02/2018 **Status:** Applied

IP Type: Patents **#:** 20180054225 **Jurisdiction:** USA

Title: Digital Multi-Band Predistortion Linearizer with Non-Linear Subsampling Algorithm in the Feedback Loop

Description: A concurrent multi-band linearized transmitter (CMLT) has a concurrent d a multi-band predistortion block (CDMPB) and a concurrent multi-band transmitter (CMT) connected to the CDMPB, The CDMPB can have a plurality of digital baseband signal predistorter blocks (DBSPBs), an analyzing and modeling (A&M) stage, and a signal observation feedback loop. Each DBSPB can have a plurality of inputs, each corresponding to a single frequency band of the multi-band input signal, and its output corresponding to a single frequency band; each output connect corresponding to an input of the CMLT. The A&M stage can have a plurality of outputs connected to and updating the parameters of the DBSPBs, and a plurality of inputs connected to either both outputs of the signal observation loop or the output of the subsampling loop and to outputs of the DBSPBs. The A&M stage can perform signals' time alignment, reconstruction of signals and compute parameters of DBSPBs.

Date: 27/07/2017 **Status:** Applied
IP Type: Patents **#:** 20170214438 **Jurisdiction:** USA

Title: MultiCell Processing Architectures for Modeling and Impairment compensation in Multi-input Multi-Output Systems

Description: 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; generating a multiple-output signal by feeding the pre-distorted multiple-input signal into a multiple-input and multiple-output transmitter; estimating impairments generated by the multiple-input and multiple-output transmitter; and adjusting the pre-distorted multiple-input signal to compensate for the estimated impairments. The present invention also relates to a pre-compensator for use with a multiple-input and multiple-output transmitter, comprising: a multiple-input for receiving a multiple-input signal; a matrix of pre-processing cells for generating a pre-distorted multiple-input signal from the received multiple-input signal; and a multiple-output for feeding the pre-distorted multiple-input signal to the multiple-input and multiple-output transmitter. The pre-processing cells are configured so as to estimate impairments generated by the multiple-input and multiple-output transmitter and adjust the pre-distorted multiple-input signal to compensate for the estimated impairments.

Date: 11/05/2017 **Status:** Applied
IP Type: Patents **#:** 20170135058 **Jurisdiction:** USA

Title: System and method for Enhanced Transmitter Efficiency

Description: A method for distortion compensation in a transmission link comprising obtaining information of an amplitude distribution of a signal prior to being transmitted by a transmitter, receiving the transmitted signal at a receiver and determining a received signal amplitude distribution, comparing the received signal amplitude distribution to the amplitude distribution of the signal prior to transmission and using results of the comparison to estimate the AM/AM non-linearity in the transmitter.

Date: 11/05/2017 **Status:** Applied
IP Type: Patents **#:** 20170134055 **Jurisdiction:** USA

Title: Signal Amplification and Transmission Based on complex Delta Sigma Modulator

Description: Apparatuses and methods for power amplification and signal transmission using complex delta-sigma modulation are disclosed. In one embodiment, a complex delta sigma modulator unit comprising a complex polar quantizer within an integrator loop is disclosed. The complex polar quantizer quantizes the envelope of a complex integrated signal and produces a complex quantized output signal of substantially constant envelope. The complex quantized output signal is used in deriving a complex feedback signal within the integrator loop of the complex DSM. The complex quantized output signal may be used in driving a power amplifier substantially at saturation. In some embodiments, an adjacent channel power ratio (ACPR) enhancement technique is used to reduce the quantization noise in the complex quantized output signal.

Date: 01/09/2017 **Status:** Granted
IP Type: Spin-Offs* **Jurisdiction:** Canada

Title: SmartRF Inc.

Description: SmartRF Inc. aims to develop critical integrated telecomm. Testbed RF platform large-scale MIMO fifth-generation (5G) communication systems.

9. PUBLICATIONS

Please provide information on the following:

Refereed journal publications	21
Conference proceedings	10
Books and Chapters	0
Special/Invited presentations	6
Awards	0
Theses	0

Please list details of all publications below.

Sample Formats:

Article in a collection

A.J. Albrecht, "Measuring Application-Development Productivity," *Programmer Productivity Issues for the Eighties* , 2nd ed., C. Jones, ed., IEEE CS Press, 1981, pp. 34-43.

Article in a conference proceeding

M. Weiser, "Program Slicing," *Proc. 14th Int'l Conf. Data Eng* . (ICDE 98), IEEE CS Press, 1998, pp. 439-449.

Article in a journal or magazine

I.E. Sutherland, R.F. Sproull, and *R.A. Schumaker, "A Characterization of 10 Hidden-Surface Algorithms," *ACM Computing Surveys* , Mar. 1974, pp. 1-55.

Book

W.M. Newman and R.F. Sproull, *Principles of Interactive Computer Graphics* , 1979, p. 402.

Digital Publication

R. Bartle, “Early MUD History,” Nov. 1990; http://www.ludd.luth.se/aber/mud-history.html.

NOTE: Please place an asterisk (*) before the name of graduate students and post-docs who are co-authors on the publications listed.

Journal Publications

W. Zhang*, A. Hasan*, F. M. Ghannouchi, M. Helaoui, Y. Wu, C. Yu and Y. Liu, "Concurrent Dual-Band Low Intermediate Frequency Receiver Based on the Multiport Correlator and Single Local Oscillator," IEEE Microwave and Wireless Components Letters, Vol. 28: Issue 4, pp. 353-355, 2018. [Abstract] [DOI]

W. Zhang*, A. Hasan*, F. M. Ghannouchi, M. Helaoui, Y. Wu, L. Jiao and Y. Liu, "Homodyne Digitally Assisted and Spurious-Free Mixerless Direct Carrier Modulator With High Carrier Leakage Suppression," IEEE Transactions on Microwave Theory and Techniques, Vol. 66: Issue 3, pp. 1475-1488, 2018. [Abstract] [DOI]

T. Sharma*, E. R. Srinidhi, R. Darraji, D. G. Holmes, J. Staudinger, J. K. Jones and F. M. Ghannouchi, "High-Efficiency Input and Output Harmonically Engineered Power Amplifiers," Ieee Transactions on Microwave Theory and Techniques, Vol. 66: Issue 2, pp. 1002-1014, Feb 2018. [Abstract] [DOI]

M. Noweir*, Q. Zhou, A. Kwan*, R. Valivarthi, M. Helaoui, W. Tittel and F. M. Ghannouchi, "Digitally Linearized Radio-Over Fiber Transmitter Architecture for Cloud Radio Access Network's Downlink," IEEE Transactions on

Microwave Theory and Techniques, pp. 1-11, 2018. [DOI]

P. Jaraut*, M. Rawat and F. Ghannouchi, "2-D Curtailed Harmonic Memory Polynomial for reduced complexity in Concurrent Dual-Band Modeling and Digital Predistortion with the second band at Harmonic Frequency," IET Communications, 2018. [DOI]

X. Du*, C. J. You, Y. Zhao*, X. Li*, M. Helaoui, J. Cai and F. M. Ghannouchi, "Wideband high-efficiency linearized PA design with reduction in memory effects and IMD3," International Journal of Microwave and Wireless Technologies, pp. 1-10, 2018. [Abstract] [DOI]

X. Du*, C. J. You, J. Cai, M. Helaoui, F. M. Ghannouchi, Y. Zhao* and X. Li*, "Novel Design Space of Load Modulated Continuous Class-B/J Power Amplifier," IEEE Microwave and Wireless Components Letters, Vol. 28: Issue 2, pp. 156-158, 2018. [Abstract] [DOI]

A. B. Arfi*, F. Elsayed, P. M. Aflaki, B. Morris and F. M. Ghannouchi, "Three-Level De-Multiplexed Dual-Branch Complex Delta-Sigma Transmitter," Sensors (Basel), Vol. 18: Issue 2, Feb 20 2018. [Abstract] [DOI]

T. Sharma*, P. Aflaki, M. Helaoui and F. Ghannouchi, "Broadband GaN Class-E Power Amplifier for Load Modulated Delta Sigma and 5G Transmitter Applications," IEEE Access, pp. 1-1, 2018. [Abstract] [DOI]

A. Abdelhafiz*, L. Behjat and F. M. Ghannouchi, "Generalized Memory Polynomial Model Dimension Selection Using Particle Swarm Optimization," IEEE Microwave and Wireless Components Letters, pp. 1-3, 2018. [Abstract] [DOI]

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. [Abstract] [DOI]

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. [Abstract] [DOI]

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. [Abstract] [DOI]

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 Transactions on Microwave Theory and Techniques, Vol. 65: Issue 8, pp. 2953-2963, 2017. [Abstract] [DOI]

W. Zhang*, A. Hasan*, F. M. Ghannouchi, M. Helaoui, Y. Wu and Y. Liu, "Design and Calibration of Wideband Multiport Homodyne Wireless Receivers," IEEE Transactions on Instrumentation and Measurement, Vol. 66: Issue 12, pp. 3160-3169, 2017. [Abstract] [DOI]

W. Zhang*, A. Hasan*, F. M. Ghannouchi, M. Helaoui, X. Li*, Y. Wu, L. Meng and Y. Liu, "Concurrent Dual-Band Receiver Based on the Multi-Port Correlator for Wireless Applications," IEEE Transactions on Circuits and Systems II: Express Briefs, pp. 1-1, 2017. [Abstract] [DOI]

M. Younes*, A. Kwan*, M. Akbarpour*, M. Helaoui and F. M. Ghannouchi, "Two-Dimensional Piecewise Behavioral Model for Highly Nonlinear Dual-Band Transmitters," IEEE Transactions on Industrial Electronics, Vol. 64: Issue 11, pp. 8666-8675, 2017. [Abstract] [DOI]

Z. Wang, W. Chen, G. Su, F. M. Ghannouchi, Z. Feng and Y. Liu, "Low Computational Complexity Digital Predistortion Based on Direct Learning With Covariance Matrix," IEEE Transactions on Microwave Theory and Techniques, Vol. 65: Issue 11, pp. 4274-4284, 2017. [Abstract] [DOI]

A. Vaezi*, A. Abdipour, A. Mohammadi and F. M. Ghannouchi, "On the Modeling and Compensation of Backward Crosstalk in MIMO Transmitters," IEEE Microwave and Wireless Components Letters, Vol. 27: Issue 9, pp. 842-844, 2017.

Nadia Chagtmi, Noureddine Boulejfen and Fadhel M. Ghannouchi" Augmented Hammerstein Model for Six-Port Based Wireless Receiver Calibration", IET Communications, pp. 951-960, VOL. 11, NO. 6, 2017.

S. Lajnef, N. Boulejfen, and F. M. Ghannouchi, “Cartesian Augmented Hammerstein Model for Nonlinearity and I/Q Impairments Compensation in Concurrent Dual-Band Transmitters”, IET Communications, pp. 1992-1997, VOL. 11, NO. 13, 2017.

Conference Papers

A. Hasan*, M. Helaoui and F. M. Ghannouchi, "Performance of quadrature phase shift frequency selective receiver in presence of blockers," in 2018 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet), pp. 15-182018. [Abstract] [DOI]

W. Zhang*, F. M. Ghannouchi, A. Hasan*, Y. Liu and Y. Wu, "Planar miniaturized balanced-to-single-ended power divider with arbitrary power division," in 2017 47th European Microwave Conference (EuMC), pp. 5-82017.[DOI]

D. Wang*, M. Fattouche and F. M. Ghannouchi, "Network-managed localization protocol for WiMAX," in 2017 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob), pp. 88-932017.[DOI]

D. Wang*, M. Fattouche and F. M. Ghannouchi, "Energy-efficient localization with OFDM transmission in multipath channels," in 2017 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob), pp. 76-812017.[DOI]

D. Wang*, M. Fattouche and F. M. Ghannouchi, "Bounds of mmWave-Based Ranging and Positioning in Multipath Channels," in 2017 IEEE Globecom Workshops (GC Wkshps), pp. 1-62017.[DOI]

T. Sharma*, S. Embar, D. Holmes, J. Jones and F. M. Ghannouchi, "Harmonically Engineered and Efficiency Enhanced Power Amplifier Design for P3dB/Back-off Applications," in IEEE International Microwave Symposium, Honolulu, Hawai’, 4-9 June, 2017 2017.[Abstract]

M. A. Maktoomi*, F. M. Ghannouchi and R. Vyas, "Novel Synthesis of Dual-Frequency RF Energy-Harvesting Rectifier Incorporating Coupled Lines," in 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), pp. 1-42017.[DOI]

S. Lajnef, N. Boulejfen and F. M. Ghannouchi, "Linearization of a concurrent dual-band transmitter exhibiting nonlinear distortion and hardware impairments using baseband injection," in 2017 International Conference on Information and Digital Technologies (IDT), pp. 361-3642017.

N.Chagtmi, N. Boulejfen and F. Ghannouchi, “Modeling and Performance assessment of the N-port based wireless receivers”, Proceeding of the IEEE 17th Mediterranean Microwave Symposium, 28-30/11 2017, Marseille, France.

N.Chagtmi, N. Boulejfen and F. Ghannouchi, “Design of a Dual-band Six-port

Reflectometer”, Proceeding of the IEEE 17th Mediterranean Microwave Symposium, 28-30/11 2017, Marseille, France.

Invited Talks:

Dr. Fadhel Ghannouchi presented:

July 13-14, 2017, IEEE – NATEG Workshop , Tunis Tunisia “Advanced Technology Workshop on Microwave and RF Design”. Keynote talk: RF and Microwave Transceivers for 5G Wireless and I of T applications

August 20-21, 2017

Visit University of Malaya, Kuala Lumpur, Malaysia. Invited Talk: Advanced Transmitters for 5G Wireless and Optical Communications.

December 18 2017: visit to IIIT, Delhi India and gave a talk entitled: "Advanced Transmitters for 5G Wireless Communications"

December 19: visit to IIIT, Delhi India and gave a Talk entitled: "Broadband and selective receivers for wireless and IoT applications"

December 20: visit IIT Roorkee, India invited Talk: "5G wireless Networks: Challengers and Enabling Technologies"

and December 21-23 : Short course “Behavior Modeling and impairment mitigation of Wireless transceivers.”

10. OUTREACH

Please describe community outreach activities such as meetings with trade missions/VIPs, community events, public presentations, involvement with schools, and significant media exposure. Please provide hyperlinks to media coverage, or upload photos/associated articles where possible.

PhD Student Anis ben Arfi participated in:

1. Outreach activities with the Optics and Photonics Students Society (December 19th)

2. Group Visit to the Calgary Clean Room Facility on Campus (February 9, 2018)

3. Solar panels installations in Northen Guatemala with Light Up The World (February 17 to 27, 2018)

4. Amateur Radio Club demonstration for Calgary Scouts (March 20, 2018)

5. Participation in Disaster Alley with the Calgary Amateur Radio Association (May 5th 2018)

PhD Student Tushar Sharma participated in:

1. iRadio Lab Graduate Student Initiative to Bridge the Canadian Digital Divide in Indigenous Community of CanadaiRadio Lab graduate students initiated the project on internet offering which was limited technically limited. A team of graduate students at University of Calgary affiliated to IEEE Special Interest Group on Humanitarian Technology (IEEE SIGHT) stepped in and collaborated with Bruce, a self-taught RF engineer to install equipment to set up antennas, access points, and backhaul links in the community. The team involved (including Bruce Buffalo, Tushar Sharma, David Garrett, and Anis Ben Arfi) is planning to spin off a not-for-profit organization whose goal is to bridge the digital divide in rural Alberta. Media Link: - https://www.cybera.ca/news-and-events/tech-radar/why-rural-connectivity-is-an-issue-for-every-canadian/

2. iRadio lab Graduates Founded Young Professionals in Space (www.ypinspace.com)Young Professionals in Space (YPS) is an initiative to bring scientists, practitioners, engineers and leaders of space industry and agencies together in a single venue to discuss recent research breakthroughs, technical advances, existing opportunities and emerging space technologies. The initiative which was flagged off in the year 2017 from India has spanned off in three countries including India, Israel, Spain and Canada to be the host in 2019. A team of iRadio lab involving Tushar Sharma, Anis Ben Arfi has been leading the project all over the world.

11. OTHER FUNDING RECEIVED

Using the following table, please provide information on additional funding you've <u>received</u> from various sources <u>in the previous fiscal year</u> for the period:

April 1 to March 31 (this reporting period).

This information is used to calculate the leverage ratio pertaining to the funding from AI.

Points to note:

1. Include only the total amount of funding <u>received</u> in the previous fiscal year, for the period April 1 to March 31 (this reporting period). Include any funding for which you or a Team Member are a Principal Investigator (PI) or co-PI.
2. Select the Funding Type from the drop-down provided.
3. 'Proof' is to indicate whether you have access to a proof that you are associated with the funding (e.g. your name on a contract or a letter of confirmation of funding).
4. Use the Notes area to provide any comments on the funding.

Applicant Name: Fahdel Ghannouchi
Funding Source: Canada Foundation for Innovation **Amount:** 136,830.00
Proof of Funding: Yes
Funding Description: IOF for Project #10004442

Applicant Name: Fadhel Ghannouchi
Funding Source: Other Federal Government **Amount:** 294,475.00
Proof of Funding: Yes
Funding Description: PWGSC "GaN High Power Amp Development"

Applicant Name: Fadhel Ghannouchi
Funding Source: Other **Amount:** 14,450.00
Proof of Funding: Yes
Funding Description: iRadio Lab Revenue

Applicant Name: Fadhel Ghannouchi
Funding Source: NSERC **Amount:** 116,000.00
Proof of Funding: Yes
Funding Description: Green Multi-Antenna and MIMO

Applicant Name: Fadhel Ghannouchi
Funding Source: Alberta Innovates **Amount:** 13,953.00
Proof of Funding: Yes
Funding Description: Intelligent RF Radio Technology

Applicant Name: Various
Funding Source: Other **Amount:** 270,000.00

Proof of Funding: Yes
Funding Description: Student Funding

Applicant Name: Fadhel Ghannouchi
Funding Source: Other Federal Government **Amount:** 10,000.00
Proof of Funding: Yes
Funding Description: PWGSC Nanowave

Applicant Name: Fadhel Ghannouchi
Funding Source: University (cash) **Amount:** 175,000.00
Proof of Funding: Yes
Funding Description: Salaries

Applicant Name: Fadhel Ghannouchi
Funding Source: NSERC **Amount:** 58,000.00
Proof of Funding: Yes
Funding Description: Discovery

Applicant Name: Fadhel Ghannouchi
Funding Source: NSERC **Amount:** 80,000.00
Proof of Funding: Yes
Funding Description: SPG

Applicant Name: Fadhel Ghannouchi
Funding Source: Canada Research Chair **Amount:** 200,000.00
Proof of Funding: Yes
Funding Description: Green Radio Technology

Applicant Name: M. Helaoui
Funding Source: NSERC **Amount:** 30,000.00
Proof of Funding: Yes
Funding Description: Discovery

Applicant Name: M. Helaoui
Funding Source: NSERC **Amount:** 140,000.00
Proof of Funding: Yes
Funding Description: SPG

12. FINANCIAL REPORTS

A Statement of Revenues and Expenses for each research project and program is sent to researchers by the finance department of the University Research Services Office (RSO).

Researchers should be getting a statement on a semi-annual and annual basis. Please make sure that you have returned a signed copy to the finance department so that it may be forwarded to Alberta Innovates as your official financial report.

Thank you for submitting your annual progress report.

List Of Attachments:
