DESIGN AND DEVELOPMENT OF MACHINE LEARNING AIDED 5G & BEYOND-5G WIRELESS NETWORKS USING SOFTWARE DEFINED RADIO NODES

1. Research or Technology Development

ICT (information and communication technologies) is an institutional priority at Carleton University. Located in Ottawa, the heart of Canada's ICT industry, Carleton has an established track-record in particular in wireless communications and networks, and has garnered international recognition for research, innovation, and HQP (highly qualified personnel) training in this domain.

The requested infrastructure will enable a team of Carleton researchers and their collaborators to develop novel designs for the next-generation wireless networks with a goal of rapidly moving from theory to experimentation and prototyping. This will help to keep Carleton among the global leaders in academic research in wireless communications.

The first four generations of wireless networks preceding 5G have been focused on the mobile phone. 5G technology will, for the first time, enable connectivity in and among vertical industries beyond telecommunications such as automotive (connected vehicles), health care, manufacturing, Internet-of-Things (IoT), and robotics. The 5G standardization process is almost complete. Once finalized, the standard will enable large-scale 5G deployments in the following years. With the widespread deployment of 5G networks, different connectivity capabilities, including enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC) will also become available.

5G is a flexible standard that will evolve throughout the next decade with a finer tuning of a number of 5G system parameters as the demand and requirements in vertical industries evolve and diversify. At the same time, the research community has also started envisaging the subsequent cycle, 6G, whose standardization is expected to take place in the second half of the next decade. Building on the 5G experience, 6G is expected to offer even more enhanced connectivity solutions (including higher rates, higher reliability, lower latency, increased security) to meet a broad range of specialized market demand in vertical industries. For example, around 2030, as a society we will become data-driven, enabled by nearly instantaneous, unlimited wireless connectivity (David & Berndt, 2018). This connectivity will require 100 to 1000 times faster data rates in comparison to what is available today with 4G; such rates cannot be provided even with the upcoming 5G standards (Yang et al., 2019).

The proposed research program focuses on the design and development of innovative physical layer and networking technologies, empowered by machine learning techniques, for 5G and beyond-5G wireless networks. As the communication technologies get more sophisticated, the associated complexity also increases substantially rendering the conventional signal processing techniques highly inefficient; machine learning is a new tool which is expected to help in managing the complexity in communication networks. Professor Halim Yanikomeroglu, the PI of this CFI-JELF application, led one of the largest pre-standard 5G wireless collaborative research projects in Canada, which was funded by the Ontario Government's ORF-RE program and industry partners from 2012–2016. Carleton University was the sole academic partner in this 5-year project, which had a cash budget of $1,290,000. This project alongside other University initiatives in 5G, has helped Carleton to gain substantial international recognition in 5G research.

The two co-PIs of this CFI-CELF application are Professors Ian Marsland and Chung-Horng Lung. Dr. Yanikomeroglu and Dr. Marsland have a long history of collaboration and graduate student co-supervision in advanced physical layer technologies which resulted in 15 publications and several granted patents. Dr. Lung is an expert in communication networks who has been focusing on machine learning applications in networking in the recent years. The PI and co-PIs are members of the Network 2030 team of Carleton University which is a multidisciplinary research cluster at the crossroads of ICT and social sciences. It brings together a diverse group of 19 faculty members from 4 faculties at Carleton University. Dr. Yanikomeroglu has pioneered the formation of this research cluster and he is currently the co-PI of the Network 2030 cluster.

The requested infrastructure is composed of two carefully designed wireless communication systems. Both systems include software-defined radios (SDR), which will enable flexible configuration to comply with different wireless standards in different experiments. The systems will be used to develop and test innovative designs of physical layer and networking technologies, some of which have already been introduced in the theoretical literature by the project team. Dr. Yanikomeroglu and the other team members will use the requested infrastructure for the following experimental objectives:

System-1 Objective: The design, implementation, and proof-of-concept (PoC) targeting waveform designs for beyond-5G communication networks through flexible waveform shaping, including non-orthogonal multiple-access (NOMA), sparse code multiple access (SCMA), and faster-than-Nyquist (FTN) signalling techniques.

System-2 Objective: The design, implementation, and PoC targeting the multiple-input multiple-output (MIMO) extension, which is empowered by machine learning algorithms. System-2 will contain the necessary components for a flexible and scalable approach to configure physical layer parameters in real-life settings.

Although similar concepts are being studied by other research groups through theoretical analyses or computer simulations based verification, most of these studies have been done using various convenient assumptions (such as the presence of ideal channel conditions and/or the absence of any equipment impairments). The requested infrastructure will enable actual PoC and prototype development giving the PI and the team an important advantage in the fierce international competition in beyond-5G research.

It is important to emphasize that, in addition to beyond-5G research activities, the requested infrastructure will also be used by Dr. Yanikomeroglu and the co-PIs to accelerate ongoing 5G research where the goal is to fine-tune 5G parameters towards enabling connectivity in vertical industries, such as IoT, smart cities, connected vehicles (cellular – vehicular-to-everything, C-V2X), and on factory floors. Although the emphasis in this research program has been on 5G and beyond-5G, the requested equipment can also support experimentation and prototyping within other frameworks and standards including IEEE 802.11 (WiFi), satellite communications, aerial networks, dedicated short range communications (DSRC), and wireless backhauling.

Carleton researchers collaborate closely with the Canadian and international industry partners in multidisciplinary areas due to the University's strong emphasis on innovation in systems research and engineering. Consequently, Carleton researchers have made significant contributions to the standardization of 4G LTE (ubiquitously deployed worldwide) and 5G communication protocols. With strong ties to the industry and government research labs, the

Carleton research community is thus very well-positioned to play a leading role in the global research and innovation efforts that will pave the way for 6G. The experience gained through the proposed CFI-JELF research program will better integrate the contributions from the Carleton researchers and accelerate their work on 6G standardization activities. The timely purchase of the equipment is crucial. As 5G standardization has been finalized recently, the implementation of 5G connectivity in vertical industries will start in 2020, and the research activities for beyond-5G will intensify in the coming years. Any delay in acquiring the infrastructure will result in lost opportunities for Canada and lagging behind the international competition.

System-1 Description: Waveform Design for Beyond-5G Systems

The design and development of theoretical systems with SDR nodes are proven to be effective tools in the research community. For example, the research activities led by Dr. Risto Wichman of Aalto University, Finland, and Dr. Taneli Riihonen of Tampere University, Finland, have served as a guide not solely for the practical implementation, but also for the theoretical upswing by providing a more accurate mathematical model of the considered system (Riihonen & Wichman, 1999).

One major goal of Dr. Yanikomeroglu's research program is the realization of the theoretical techniques in the contemporary literature that will likely lead the way to 6G standardization activities. The main technological contenders in the beyond-5G networks include (but not limited to) the leading physical layer innovations, FTN signaling, signal constellation design, NOMA (Saito et al. 2013), SCMA (Nikopour & Baligh, 2013), and error control coding techniques, with a specific focus on polar codes (Arikan, 2009). In the area of FTN signalling, the PI's team has recently proposed practical receiver structures (Bedeer et al., 2019) that can be used as a starting point within the PoC designs. This is a re-discovered technique since the work done at AT&T Bell Labs in 1970s (Mazo, 1975), offers significant potential to improve the transmission rates in a given bandwidth (Liveris & Georghiades, 2003; Anderson et al., 2013).

One of the main building blocks of physical layer technologies is the signal constellation design to be used in the digital modulators and demodulators. In regards to the constellation design, the team has demonstrated the impact of constellation in terms of signal-to-noise ratio (SNR) gain, leading to either higher data rates or more energy-efficient transmissions (Ilter & Yanikomeroglu, 2018). This work theoretically demonstrates that a significant SNR gain can be possible through an intricate signal constellation design. Validations of such gains in practice will be of significant value and will likely trigger further research in this area.

Another technological contender for beyond-5G networks addresses the spectrum sharing possibilities. Conventional orthogonal (non-overlapping) resource sharing techniques have been shown in the literature to be inefficient in a wide range of application scenarios when compared to the non-orthogonal resource sharing technique. The research team at Carleton has demonstrated important contributions in the area of NOMA, significantly shaping the literature. Specifically, the project team investigated the performance limits and proposed design approaches within this novel multiple-access paradigm, both in terms of the code-domain and the power-domain perspectives (Abu Mahady et al., 2019). In particular, SCMA will also be considered in the target system as a promising code-domain NOMA technique. The project team also provided a guide to design SCMA systems, and their associated performance analysis in several research works, with a special focus on constellation design (Vameghestahbanati et al, 2019). In addition, the research team has carried out research activities related to error control coding with a special focus on the contemporary polar codes (Khoshnevis et al. 2019). The theoretical background of the PI and the co-PIs is sufficient to successfully pursue the project activities targeting the PoC level designs and developments in physical layer technologies.

Dr. Yanikomeroglu and the co-PIs will use the requested infrastructure to implement the aforementioned techniques in a reconfigurable manner by using LabVIEW software as the main tool. This tool enables the quick reconfiguration of the radio parameters on the transmitter and the receiver. The proposed infrastructure of the first system also enables arbitrary waveform generation techniques, so that a combination of the aforementioned techniques with novel approaches can also be investigated using the same hardware components. The system will allow the Carleton team to understand the data transmission limits using a diverse set of signalling techniques on the transmitter side, and to also evaluate the reception performance and assessment of the computational complexity of the receiver architectures. Dr. Yanikomeroglu, his co-PIs, and their research team members will use the requested infrastructure to capture further insights about the impact of hardware impairments, such as carrier timing/frequency offsets, the in-phase/quadrature imbalance and power amplifier nonlinearity on system performance. The research team will therefore be able to design new remedies that resolve such impairments. They will also be able to quantify and report on the impact of the investigated approaches, generating significant know-how on practical aspects which are almost never taken into account in theoretical studies. By uncovering the data transmission limits through experimentally verified novel advanced technologies (including machine learning), Carleton University will maintain its leadership in the area of wireless communications and keep Canada at the forefront of international efforts in a highly competitive research area.

System-2 Description: Machine Learning Aided Multi-Antenna System

MIMO systems make effective use of large-scale antenna arrays with time-effective deployment and reduced complexity in various environments. This enables an additional degree of freedom that emerges from the spatial dimension (Sampath et al. 2002). Although a substantial amount of literature exits in MIMO systems, experimental studies reveal several overly simplistic assumptions that are commonly made in the theoretical literature. Research activities led by Dr. Rui Dinnis of NOVA University Lisbon, Portugal, include several experimental studies in MIMO systems including a comprehensive survey (Mokhtari et al., 2019). These studies clearly demonstrate the need to consider the hardware impairments in theoretical models to accurately study the overall system performance.

The project team already has several contributions in the field of MIMO system design targeting simplified receiver architectures (Vaezy et al. 2019). The number of parameters that need to be configured increases with the number of transmit and receive antennas. The proper calibration and tuning of these parameters becomes a very complex problem from a computational perspective. The use of machine learning is expected to provide low complexity solutions to determine the proper values for the design parameters without compromising the system performance. In highly complex problems, the data-driven approaches facilitated by machine learning are more feasible to implement in comparison to the conventional model-driven approaches where developing adequate models in real-time may be exceedingly difficult.

Within the scope of the proposed research program, the team will optimize both the transmitter and the receiver structures of MIMO systems using machine learning techniques. The project team, in particular, co-PI Dr. Lung, has experience in machine learning algorithm design (Zaman et al., 2018; Rahman et al. 2019). In addition, innovative and functional communication systems will be designed and developed, which will also combat the hardware related transmission impairments as in the previous page.

The algorithms that will be designed by the Carleton research team in accordance with the research activities targeted by this research program will develop as the research activities progress beyond solely theoretical studies and simulation-based analyses. This will provide them a more in-depth understanding of the intricate design of sophisticated wireless systems. Through the designed and implemented framework, the PI and the team aim to offer the required flexibility and self-renewability in terms of communication system error performance and management aspects. They will specifically focus on the channel estimation and feedback delay issues, which are inevitable in testbed deployments, which will provide an opportunity for machine learning based approaches to outperform the maximum-likelihood techniques that do not consider any hardware impairments. Furthermore, machine learning based physical layer parameter selection problems will be extended to the joint modulation selection and configuration updates, and real-time machine learning based algorithms will be implemented. Cognitive aspects, including adaptive transmission and adaptive band selection problems will also be considered in the testbed design.

The target set-up is modular by design, and can be applied for diverse applications ranging from Internet-of-Things (IoT), smart cities, cellular vehicle-to-vehicle and vehicle-to-infrastructure (C-V2X) systems. Novel experimental research to test beamforming techniques for new use cases, such as the future unmanned aerial vehicles (UAVs) and V2X services, is very important, due to the fact that 5G and beyond-5G networks will mainly be catering to the vertical industries as new markets.

2. Researchers

Dr. Yanikomeroglu (PI), Dr. Marsland (co-PI), Dr. Lung (co-PI), and their research team members will be the primary users of the requested infrastructure. In addition, a number of collaborators of the PI & co-PIs will have access to the experimental set-up as highlighted below.

Dr. Halim Yanikomeroglu (PI) is a Full Professor in the Department of Systems and Computer Engineering at Carleton University. He has supervised 22 PhD and 28 MASs students (all completed) and 60 PDFs and visiting researchers from around the world. He has coauthored around 400 peer-reviewed research articles, 138 of which appeared in the IEEE journals which are arguably the world's most authoritative periodicals in the subject area of this application and are the most difficult to publish in (IEEE stands for the Institute of Electrical and Electronics Engineers, which is the world's largest professional organization with about half a million members around the world). Dr. Yanikomeroglu's work has received over 12,700 citations, resulting in an h-index of 45. He is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), the Engineering Institute of Canada (EIC), and the Canadian Academy of Engineering (CAE). He is a Distinguished Speaker for the IEEE Communications Society and the IEEE Vehicular Technology Society on 5G/6G wireless technologies, and has frequently presented tutorials at the leading international IEEE conferences (32 times). He has had extensive collaboration with partners from the Canadian and international industry, which has resulted in 34 granted patents (all from the collaborative research conducted at Carleton). During 2012-2016, he led one of the largest academic-industrial collaborative research projects on prestandards 5G wireless, sponsored by the Ontario Government and industry partners. Dr. Yanikomeroglu is currently serving as the steering committee chair of one of the world's leading technical conferences in the wireless domain, IEEE Wireless Communications and Networking Conference (WCNC). He served as the chair of the IEEE Technical Committee on Personal Communications. He has served on the editorial boards of the IEEE Transactions on Communications, IEEE Transactions on Wireless Communications, and IEEE Communications Surveys & Tutorials, and co-edited a number of special issues. Dr. Yanikomeroglu is a recipient of the IEEE Communications Society Wireless Communications Technical Committee Recognition Award in 2018. He is also a recipient of the IEEE Ottawa Section Outstanding Service Award in 2018, the IEEE Ottawa Section Outstanding Educator Award in 2014, Carleton University Faculty Graduate Mentoring Award in 2010, the Carleton University Graduate Students Association Excellence Award in Graduate Teaching in 2010, and the Carleton University Research Achievement Award in 2009 and 2018.

Dr. Ian Marsland (co-PI) is an Associate Professor in the Department of Systems and Computer Engineering at Carleton University. From 1987 to 1990, he was with Myrias Research Corporation, Edmonton, AB, Canada, and CDP Communications Inc., Toronto, ON, Canada, as a Software Engineer. His research interests fall in the area of wireless digital communication and physical layer technologies. He has been actively pursuing research activities including co-supervision of PhD students with Dr. Yanikomeroglu, which resulted in 15 coauthored publications (8 IEEE journal papers and 7 IEEE conference papers). Dr. Marsland will be contributing towards the physical layer signalling designs over the target infrastructure, supervising the system design activities and also providing theoretical support for the performance evaluation of the designed systems. His industrial experience will also be a strong asset through the design processes of System-1 and System-2; this will speed up the test-bed installation process, enabling the project team to rapidly start the experimental activities.

Dr. Chung-Horng Lung (co-PI) is a Full Professor in the Department of Systems and Computer Engineering at Carleton University. Dr. Lung was with Nortel Networks from 1995 to 2001. At Nortel, he worked in the Software Engineering Analysis Lab (SEAL) as the lead for the Software Architecture Analysis group and the Optical Packet Interworking (OPi) on IP/MPLS traffic engineering. During his activities at Nortel, Dr. Lung received several awards for the recognition of this work including the Vice President's Award of Excellence. In September 2001, Dr. Lung joined Carleton University. In line with his research interests (which include software engineering, computer networks, cloud computing, wireless ad hoc and sensor networks, network-based control systems, and machine learning), Dr. Lung will be contributing towards the design of the network-layer aspects of the target PoC activities. This experience on the networking layer, also enriched by his industry experience, will shape the designs of the communication protocols, providing guidance in high-layer signalling designs and also contributing towards the performance assessment activities.

The PI and co-PIs already have extensive research outcomes in the waveform design, the multi-antenna system design, as well as in the networking protocol design areas in terms of numerous highly-cited publications, PhD dissertations, and granted patents.

Other Collaborators:

Dr. Gunes Kurt (Full Professor, Istanbul Technical University [ITU], Turkey) is a Visiting Professor in the Department of Systems and Computer Engineering, Carleton University, during the 2019-2020 academic year. Dr. Kurt has a similar wireless networks lab at ITU (arguably the most advanced academic wireless networking infrastructure in Turkey). Dr. Kurt is in the process of being appointed as an Adjunct Research Professor at Carleton. Dr. Yanikomeroglu and Dr. Kurt plan to engage in a long-term collaboration, mainly on experimental research. Once the requested infrastructure has been installed at Carleton, PhD students from Dr. Kurt's lab in ITU will visit Carleton to actively work on complimentary projects supported by TUBITAK (the Scientific and Technological Research Council of Turkey), which provides generous support for postdoctoral fellows and PhD students for knowledge mobility.

The requested infrastructure will support Dr. Yanikomeroglu's continuing collaborations with Dr. Claude D'Amours and Dr. Abbas Yongacoglu, faculty members in the School of Electrical Engineering & Computer Science at the University of Ottawa. Dr. Yanikomeroglu already has 8 publications coauthored with Dr. Yongacoglu and Dr. D'Amours. Co-supervision of graduate students between faculty members of the two universities are enabled through the Ottawa-Carleton Institute for Electrical and Computer Engineering (OCIECE), which aims to combine the graduate programs and research activities of Carleton University and uOttawa.

High quality international collaboration opportunities are expected to emerge as one of the outcomes of the proposed research program. As such, in addition to the above-listed ones, the target infrastructure is expected to facilitate new collaborations, including research visits to Carleton University from both within and outside Canada. The expenses of the visiting overseas researchers are often covered by the talent mobility funds of the visiting researchers' governments and universities.

Statement on equity, diversity and inclusion: Dr. Yanikomeroglu, Dr. Marsland, and Dr. Lung have considered equity, diversity, and inclusion when forming the team. The PI, co-PIs, and collaborators have the required expertise and represent multiple disciplines, ethnic backgrounds and career stages. The PI and co-PIs are strong supporters of equity, diversity, and inclusion, including the recruitment of visible minorities and gender balanced HQP. For instance, five of the eight PhD students in PI's current research team are women. Moreover, three of these five women PhD students are major award winners (R. Alkurd: Vanier Canada Graduate Scholarship; M. Vameghestahbanati: TRIO award; I. Bor-Yaliniz: appeared in "2019 Rising Stars in Networking and Communication" [the only Canadian woman so far in the annual list of ten produced for the last three years]). Equity, diversity, and inclusion will be considered as a top priority in future HQP recruitments as well.

3. Infrastructure

In this research program, the proposed infrastructure is composed of SDR components programmed by the LabVIEW software platform. The SDR structure allows some or all of the physical layer functions to be software definable. The software defined nature of the physical layer will allow the PI and co-PIs to test their innovative designs simply by reconfiguring the software that controls the SDR nodes. In addition to enabling the design and test of custom waveforms that will be developed during the project activities, the LabVIEW platform and the SDR nodes provide support to several standards including 4G Long Term Evolution (LTE), IEEE 802.11 b/g/n/ac/ax (WiFi), and C-V2X systems. The requested infrastructure can be used for a comprehensive evaluation system of a working 5G New Radio (NR) system to demonstrate its feasibility and practicality. Additionally, its flexible configuration will allow the PIs and their collaborators to investigate the impact of changing physical layer parameters of standards in terms of the target performance metrics and the constraints. The real-time tests are known to increase researchers' understanding of the system designs, providing the necessary in-depth knowledge to take the field further (Sampath et al. 2002).

The requested infrastructure focuses on two distinct yet complementary systems: System-1 focuses on the waveform design for 5G and beyond-5G networks; System-2 enables the design of machine learning aided multi-antenna system. System-1 mainly targets the PoC level design and development with the high-end transceiver to enable the design of custom waveforms for beyond-5G networks through flexible waveform shaping. System-2 extends the waveform analysis to MIMO set-ups with machine learning based solutions to assign physical layer parameters and select waveforms in a cognitive manner. LabVIEW software will be used in both systems as a graphical system design tool. Both systems will allow the PI and the team to perform experimental evaluations during which their research teams will optimize parameters for various conditions, providing them the opportunity to investigate the performance limits.

The requested infrastructure will enable Dr. Yanikomeroglu and the team to design SDR based PoC designs for addressing research problems that are currently being investigated by the research community in a theoretical or simulation based manner. The requested platform integrates software and hardware solutions to enable development of an emulator system that is capable of real-time wave shaping at a reasonable cost even in a university laboratory. The SDR based PoC deployments will unearth the associated technical problems by providing Dr. Yanikomeroglu and the team the opportunity to observe real-life challenges and to propose realistic and practical solutions. Additionally, based on the outcome of his experiments, new mathematical models will be deduced that will enable him and his research team to advance theoretical considerations. SDR-based solutions will help them to transform their novel wireless research ideas into functioning prototypes. Their main PoC designs will focus on two main research trajectories: waveform design for beyond 5G networks, and machine learning aided multi-antenna communication system. While their focus mainly lies in the given directions, the flexible architecture of the SDR based components will ensure maximum utilization. To the best of the PI and co-PIs' knowledge, there is no 5G-complying experimental research facility at Carleton University or at the University of Ottawa. By using the requested infrastructure, several new opportunities related to the practical and theoretical performance aspects are expected to emerge for the PI and the entire team to pursue.

Specifically, the new equipment will allow the PI and the team to use rapid prototyping SDR tools and the LabVIEW Communications System Design Suite to develop a flexible physical layer interface. The proposed two systems provide the most common platform in academic wireless experimental labs; this will enable and facilitate collaborations with other universities worldwide. The resulting prototypes can support waveform generation for diverse systems such as WiFi, Bluetooth, ZigBee, 4G LTE, and 5G NR.

System-1: Waveform Design for Beyond-5G Systems
(Total: $229,076; Cash: $179,610; In-Kind: $49,466)

This system is for the development and implementation of a PoC design, with a focus on waveforms, for 5G and beyond-5G communication networks. The targeted innovation is the deployment of a novel real-time channel estimation and equalization algorithm, combined with a real-time iterative detector. The transmitter and the receiver with custom-waveform support will be based on a vector signal transceiver (VST) module. This module enables data transmission up to 6 GHz with 1 GHz of instantaneous bandwidth for signalling from 2.2 GHz to 6 GHz, and it will function as a flexible real-time waveform generator. This module is selected due to its state-of-the art operational characteristics that can address the requirements associated with advanced waveform design (Objective 1): The module has a low phase noise, less than -102 dBc/Hz up to 4 GHz with 20 kHz offset, self-calibration °C with ± 10°C temperature variations, along with a stable frequency response at high instantaneous bandwidth. It has the capability to combine a vector signal generator, vector signal analyzer and high-speed serial interface with FPGA-based real-time signal processing; all these features are essential for the analysis of 5G waveforms and the design of beyond-5G waveforms. The same module will be used as the transmitter through the RF-out port and the receiver through the RF-in port. This state-of-the-art transmitter/receiver will make it possible for the project team to investigate novel designs for beyond 5G waveform design activities that will be important for future high performance waveform designs, transmission and reception processes with a high fidelity. This system uses the same SDR module as the transmitter and the receiver hence tight synchronization is possible between two ends. The physical distance between the transmit and receive antennas will be introduced through the use of low loss RF cables.

The NOMA and SCMA signals will be emulated in the transmitter to investigate the performance of multiple users in the network. Note that this module can also be used for spectrum monitoring and signal analysis purposes.

System-2: Machine Learning Aided Multi-Antenna System
(Total: $165,887; Cash: 120,993$; In-Kind: $44,894)

The target MIMO Prototyping System is a fully modular, real-time MIMO testbed with an open and reconfigurable ready-to-run software reference design. The requested version includes the hardware and software needed to build versatile, flexible, and scalable MIMO prototypes capable of real-time, two-way communications. This configuration also supports a machine learning platform through the LabVIEW software – a feature essential for the envisioned flexible design in Objective 2. This MIMO Prototyping System, based on NI-2944/54 USRP (universal software radio peripheral) devices can support up to 8 single-antenna users simultaneously as well as a single multi-antenna user with up to 8 antennas. The antennas and their transmission parameters can be selected by using machine learning algorithms according to the target performance metric. It is also possible to expand the set-up to support anticipated research challenges that could involve 128 antennas by adding SDR components. The USRP Software Defined Radio Device is a set of tunable USRP transceivers for prototyping wireless communication systems, each supporting a frequency range up to 6 GHz with up to 160 MHz of instantaneous bandwidth. The set-up can also support LTE relaying, RF compressive sampling based signaling, spectrum sensing, cognitive radio, beamforming, and direction finding. System-2 contains PXIe-7976R FlexRIO FPGA coprocessor modules to address the real-time signal processing requirements for the MIMO prototyping. Each PXIe-7976R contains a Kintex-7 410T FPGA that can enable direct FPGA designs as well. Each FlexRIO module can receive or transmit data across the backplane to each other and to all the USRP RIO SDRs with a latency of less than 5 µs, providing a suitable setting for real-time tests. Dr. Yanikomeroglu and the team will use USRP devices for transmission and reception, programmed using LabVIEW. The plans also include developing a channel sounding testbed using USRPs and LabVIEW software.

Synchronization of the SDRs is an essential aspect of this system for proper functioning between different devices. The synchronization of each module will be enabled by a common 10 MHz reference clock and a digital trigger. The reference clock signal will be generated by the PXIe-6674T Synchronization Module in the chassis, which is using an oven-controlled crystal oscillator to produce a stable and accurate 10 MHz reference clock with 80 ppb accuracy. This signal is used to feed the SDRs, thereby ensuring that each antenna has access to the same 10 MHz reference clock and master trigger. As a result, the timing and synchronization architecture offer very precise control of each radio/antenna element from the hardware perspective, enabling a phase-coherent operation. Software calibration techniques will be used by the PI and co-PIs to compensate the carrier frequency offset in order to sufficiently align the channels to achieve the target performance at the receiver modules.

The presence of multiple users with multiple antennas can be emulated with this system, providing a MIMO design environment. Both uplink channels and the downlink channels can be independently considered for specialized modulations and waveforms (such as the generalized spatial modulation (GSM), index modulation, adaptive numerology, SCMA, and FTN techniques). The main innovative feature of this generalized MIMO design environment will be the introduction of the machine learning algorithms in the parameter configuration phase of the wireless systems. The target machine learning approaches can be jointly implemented on the requested software interoperable components. Specifically, convolutional neural networks (CNN) and recursive neural networks (RNN), and decision-tree (DT) based approaches will be considered at the initial phase. Hence, Dr. Yanikomeroglu and the team will be able to design and develop machine learning-based 5G/6G system prototypes.

It must be noted that the components of both systems can also be used together. Controlled by the LabVIEW interface, System-1 and System-2 can be combined due to their modular, flexible hardware components. This capability will provide the applicant and his research team the opportunity to consider a wide range of applications. For example, by using System-1 as the base station and the SDRs of System-2 as the user equipment a wireless communication scenario can be deployed. Once again, both uplink and downlink configurations can be studied, integrating the machine learning aided control mechanisms to develop new techniques to satisfy user demand associated with beyond 5G networks.

4. Institutional Commitment and Sustainability

4.1 Institutional Commitment

According to the Shanghai Rankings 2019, Carleton ranks #33 in the world in the area of Telecommunications Engineering, and #3 in Canada (after UBC and uWaterloo). Carleton is the only university in Canada offering a Bachelor of Engineering (BEng) program in Communications Engineering.

With a $50,000 investment, Carleton University established the Network 2030 multidisciplinary research cluster in early 2019. Network 2030 brings together 19 faculty members from 7 academic units in 4 faculties (Dr. Yanikomeroglu is the co-PI of Network 2030, and Dr. Marsland and Dr. Lung are members of the research cluster). The rich, complementary and broad range of research interests of the Network 2030 team members will allow the cluster to study the highly complex and multidisciplinary, technical and societal dynamics of the information and communication networks of the 2030s, which will have strategic significance to Canada and unprecedented importance to society and the individual. The primary goal of Network 2030 is to help in maintaining Carleton University's established track-record in research, innovation, and HQP training, in the ICT area. The allocation of this CFI-CELF fund to the research program of Dr. Yanikomeroglu also demonstrates the University's strong commitment for research in wireless networks, in particular on 5G and beyond-5G.

In support of the proposed research program, and to promote active collaboration between the wireless communications researchers, the Department of Systems and Computer Engineering will be dedicating part of the research lab located in room 4038 in MINTO CASE (Centre for Advanced Studies in Engineering) Building to the proposed infrastructure. The Department is investing $15,000 in the renovation of this lab space for the secure housing of the new infrastructure in an 8 feet x 10 feet glass cabinet. The renovation will support easy access to the new infrastructure.

Carleton University has recently joined the Photonics Satellite Communications Consortium Canada (led by National Research Council Canada, NRC) as a Tier-1 founding member with a total commitment of $50,000 cash and $875,000 in-kind contribution over the next 5 years. The University's presence in the Consortium (which has a research focus on inter-satellite links and the interoperability between 5G & beyond-5G networks and satellite networks) is a further demonstration of the University's commitment to research excellence in wireless networks.

The proposed infrastructure and the associated research program will also support two other high-priority research initiatives at Carleton University in the ICT domain: Autonomous Systems Research Cluster, and Connected Autonomous Vehicles (CAV) Research Cluster; Dr. Yanikomeroglu is a member of both research clusters.

4.2. Sustainability of Infrastructure

The infrastructure will be housed in a research lab (4038 MC). The lab will feature a secure glass enclosure to store the equipment so that it remains in good working order for at least 5 years. While the experiments are conducted, the equipment will be taken out of the closure as necessary. The secure enclosure, two wired Ethernet connections, IEEE 802.11ac compatible routers, security cameras and swipe card system are also included in the renovations to be paid by the Department of Systems and Computer Engineering (approximately $15,000).

The use of the infrastructure will be maximized as the wireless team at Carleton will continue to recruit and train highly motivated HQP (Honours, Master's, PhD, post-docs) that will be funded by various research projects conducted by the PI and the co-PIs. The researchers will collectively supervise approximately 8 graduate students each year who will be directly benefiting from the research infrastructure, in addition to approximately 6 undergraduate HQP involved in capstone research projects each year. This will ensure that the requested infrastructure remains in daily use by wireless researchers and their well-trained research teams. PI has extensive experience in leading large teams of researchers and large-scale collaborative research projects; this experience will help in managing and coordinating the usage of the infrastructure when more than one research team conduct experiments. Particular emphasis will be placed on equity and diversity to ensure recruitment of gender-balanced HQP including under-represented groups.

Since there will be several users of the infrastructure, a time scheduling mechanism will be put into place. A postdoctoral fellow (PDF) will be responsible for managing access to the equipment and scheduling use by the HQP and researchers directly involved in the proposed research program, as well as the PI's collaborators. This professional responsibility will only require a small time commitment from the PDF and will be covered using the infrastructure operating fund (IOF; approximately $5,000 per year). The cost of minor supplies, such as cables (approximately $2,000 per year), as well as the cost of minor maintenance & repair (approximately $2,000 per year) will also be covered using IOF.

5. Benefits to Canada

The proposed experimental infrastructure will be unique at Carleton University. Although a substantial amount of 5G research is currently being carried out in Canadian universities, the overwhelming majority of this work is computer-based modelling, design, and performance analysis. Moreover, since the 5G standards have been finalized very recently, to the best of the PI's and co-PIs' knowledge, the existing wireless communications labs in Canadian universities are likely not 5G-complying yet. In other words, the PI and co-PIs are not aware of any academic lab in the country with comparable facilities.

"Connected" and "autonomous" are the two complementary keywords for the 5G and beyond-5G era characterized by the presence of very high-quality wireless connectivity (with very high data transfer rates, ultra-low latency, and very high reliability) that will be almost ubiquitous for all wireless network users. Therefore, Dr. Yanikomeroglu is placing strong emphasis on machine-learning based functionalities in his proposed experimental lab, which will be established through this CFI-JELF funding.

5.1. Enhancement of Training Environment

The proposed infrastructure will create unparalleled learning and training opportunities for HQP, and thus will benefit the Canadian ICT industry which has a very strong presence in Ottawa, in particular in the area of telecommunications. In addition, the outcomes of the proposed research program will directly contribute to ongoing R&D in Ottawa in the vertical industries which will directly benefit from the 5G and beyond-5G connectivity. Moreover, this research program will help Carleton retaining its reputation as an international hub of research and innovation in ICT, pioneering the related research activities.

Among the 5G-related vertical industries, it is especially worth emphasizing the companies working on CAV (connected and autonomous vehicles) and related technologies. Kanata North Technology Park, the largest tech park in Canada, which is also host to one of the largest CAV clusters in Canada with 70 companies working on CAV and related technologies. Specifically, the outcomes from Dr. Yanikomeroglu's proposed CFI-JELF program will contribute to communication system designs and, in collaboration with industry partners, his team's work can be tested on vehicles at Ottawa's recently opened L5 CAV test facility. The L5 facility offers world-class integrated testing grounds for the safe implementation of CAV. On site, vehicle-to-everything (V2X) testing, validation and demonstration are enabled on both public and private test tracks, in Ottawa's four-season climate including the harsh winters. The Ottawa L5 facility is equipped with dedicated short range communications (DSRC), Wi-Fi, 4G LTE, and 5G networking infrastructure, making it the first integrated CAV test environment of its kind in North America.

Experimentation and prototyping activities will provide a unique training experience for HQP, and will help in attracting top talent to Canada and Carleton University, and in retaining them at all levels from graduate students, to PDFs and professors. The requested infrastructure will boost HQP training in the areas of wireless communication systems design for beyond-5G networks. Within the research activities targeting Objective 1 and Objective 2, the systems designed using the infrastructure will support exciting opportunities for HQP to design, learn, participate in, and apply theoretical models that further contribute to cutting-edge literature. This will give a complete set of complementary skills to HQP in wireless system modelling and design, making active HQP attractive to the ICT employers through their unique design experiences.

The innovative hands-on nature of the proposed research program will provide opportunities for the co-supervision of graduate students between different departments at Carleton and will help to merge field-specific research silos. The students will benefit from the co-supervision activities between the PI and co-PIs, as well as between them and their collaborators at Carleton (such as the Network 2030 cluster members), uOttawa and abroad. The proposed infrastructure and the research program is expected to attract a high number of international visiting researchers at all levels.

Prototyping and demonstration activities are expected to create new research and collaboration opportunities with industry as well the EU projects, Canada National Defence's Innovation for Defence Excellence and Security (IDEaS) projects, and the ENCQOR 5G projects of the Ontario and Quebec governments and industry. All these projects highly value experimental work and demonstrations.

5.2. Benefits to Canadians and Expected Significance

The wireless industry is one of the essential pillars of the ICT sector in Canada. An industry report commissioned by the Canadian Wireless Telecommunications Association (CWTA) and developed by Accenture Strategy, (CWTA, 2018) states that the "*deployment of 5G networks across Canada will lead to the creation of hundreds of thousands of new jobs. Specifically, more than 150,000 short-term jobs are likely to be created between 2020 and 2026 while the networks are being deployed, and the estimated $26 billion investment by facilities-based carriers required to deploy the networks is likely to create 250,000 more permanent jobs annually by 2026*."

To remain competitive at the international level, Canada must invest in innovation that continuously pushes research into next generation wireless networks to the forefront of the field; Leadership in 5G and beyond-5G research will enable the Canadian industry to have access to the much sought-after talent in the ICT area **–** this is crucial to the Canada's economy.

Moreover, this leadership in research will speed up Canada's embracing of many of the advanced technologies in vertical industries (such as CAV) before most other countries. Universal connectivity, compounded by autonomous operation (enabled by machine learning & artificial intelligence), has the potential to enhance Canadians' quality of life, efficiency, and productivity in unprecedented ways. Therefore, the envisioned leadership in research will indeed benefit Canadians from coast to coast to coast.

5.3. Potential End Users and Plans for Knowledge Mobilization

The end users for this research will primarily be industrial and research partners. The developed novel (PoC) implementations of the wireless communication system designs can enable both academic and industrial researchers to observe interactions between theoretical designs and real-life challenges due to hardware impairments, enabling rapid prototyping, leading the path to commercial products. The PI and co-PIs have extensive experience working with industry and applying their research beyond the lab; Dr. Yanikomeroglu, for example, has 34 granted patents that resulted from collaborative research with industry during his tenure at Carleton University.

Carleton University is a member of Research Impact Canada (RIR), a knowledge mobilization pan-Canadian network of 17 universities committed to maximizing the impact of academic research for the social, economic, environmental and health benefits of Canadians. Through this membership, the PI and co-PIs are committed to developing institutional capacities to further support knowledge mobilization by developing and sharing knowledge mobilization best practices, services and tools.

The PI and co-PIs will also take advantage of the FED (Faculty of Engineering and Design at Carleton) Talks program to engage the community in open discussions about the ultimate goals of their research program and familiarize the public with its innovative and impactful outcomes.

The PI and co-PIs will accomplish knowledge mobilization through the presentation of high-quality publications, invention disclosures or patent applications, or a combination of these activities, and HQP thesis findings at scientific conferences, regional workshops, invited seminars, and reports to non-academic research partners and interested stakeholders. For example, the Dr. Yanikomeroglu has organized 25-30 technical seminars at Carleton University per year for the last 10 years. These activities will ensure that the research output will be timely, relevant, and accessible to help lead research activities in the wireless research related academic community and the telecommunications industry and help Canada build its global reputation for excellence in this domain.

6. References

(Abu Mahady et al., 2019) I. Abu Mahady, E. Bedeer, S. Ikki, H. Yanikomeroglu, “Sum-rate maximization of NOMA systems under imperfect successive interference cancellation”, *IEEE Comm. Letters*, vol. 23, no. 3, pp. 474-477, Mar. 2019.

(Anderson et al., 2013) J. B. Anderson, F. Rusek, V. Öwall, "Faster-than-Nyquist signaling," *Proceedings of the IEEE*, vol. 101, no. 8, pp. 1817-1830, Aug. 2013.

(Arikan, 2009) E. Arikan, "Channel polarization: A method for constructing capacity-achieving codes for symmetric binary-input memoryless channels." *IEEE Trans. Info. Theory*, vol. 55, no. 7, pp. 3051-3073, 2009.

(Bedeer et al., 2019) E. Bedeer, H. Yanikomeroglu, M.H. Ahmed, “Low-complexity detection of M-ary PSK faster-than-Nyquist (FTN) signaling”, in *IEEE WCNC Workshops 2019*.

(CWTA, 2018) https://www.cwta.ca/blog/2018/07/10/5g-wireless-could-add-40-billion-in-annual-gdp-and-250000-permanent-new-jobs-to-canadian-economy-by-2026-accenture-report-finds/ (Access date: 09/26/2019)

(David and Berndt, 2018) K. David, H. Berndt, “6G Vision and Requirement,” *IEEE Vehic. Tech. Mag*., vol. 13, no. 3, Sept. 2018, pp. 72–80.

(Ilter & Yanikomeroglu, 2018) M.C. Ilter, H. Yanikomeroglu, “Convolutionally coded SNR-adaptive transmission for low-latency communications”, *IEEE Trans. on Vehicular Tech.*, vol. 67, no. 9, pp. 8964-8968, Sep. 2018.

(Khoshnevis et al., 2019) H. Khoshnevis, I. Marsland, H. Jafarkhani, H. Yanikomeroglu, "Space-time signal design for multilevel polar coding in slow fading broadcast channels", *IEEE Tran. on Comm.*, vol. 67, no. 9, pp. 5940-5952, Sep. 2019.

(Liveris & Georghiades, 2003) A.D. Liveris, C.N. Georghiades, "Exploiting faster-than-Nyquist signaling", *IEEE Trans. on Comm.*, vol. 51, no. 9, pp. 1502-1511, 2003.

(Mazo, 1975) J.E. Mazo, "Faster-than-Nyquist signaling," *The Bell System Tech. Journal*, vol. 54, no. 8, pp. 1451-1462, Oct. 1975.

(Mokhtari et al., 2019) Z. Mokhtari, M. Sabbaghian, R. Dinis, "A survey on massive MIMO systems in presence of channel and hardware impairments" *Sensors*, vol. 19, no. 1, 2019.

(NI, 2016) National Instruments Case Study - http://sine.ni.com/cs/app/doc/p/id/cs-17101# (Access date: 09/26/2019)

(Nikopour & Baligh, 2013) H. Nikopour, H. Baligh. "Sparse code multiple access", in *2013 IEEE 24th Annual Int. Symp. on Personal, Indoor, and Mobile Radio Comm. (PIMRC)*, 2013.

(Rahman et al. 2019) O. Rahman, M.A.G. Quraishi, C.-H. Lung, "DDoS attacks detection and mitigation in SDN using machine learning," *IEEE World Congress on Services* (*SERVICES*), Milan, Italy, 2019, pp. 184-189.

(Riihonen & Wichman, 1999) T. Riihonen, R. Wichman. "Full-duplex in wireless communications", *Wiley Encyclopedia of Electrical and Electronics Eng.*, pp. 1-24, 1999.

(Saito et al. 2013) Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access", *IEEE VTC2013-Spring*.

(Sampath et al. 2002) H. Sampath, S. Talwar, J. Tellado, V. Erceg, A. Paulraj, "A fourth-generation MIMO-OFDM broadband wireless system: Design, performance, and field trial results," *IEEE Comm. Mag.*, vol. 40, no. 9, pp. 143-149, 2002.

(Vaezy et al. 2019) H. Vaezy, M.J. Omidi, M.M. Naghsh, H. Yanikomeroglu, "Energy efficient transceiver design in MIMO interference channels: The selfish, unselfish, worst-case, and robust methods", *IEEE Trans. on Comm.*, vol. 67, no. 8, pp. 5377-5389, Aug. 2019.

(Vameghestahbanati et al., 2019) M. Vameghestahbanati, I. Marsland, R.H. Gohary, H. Yanikomeroglu, "Multidimensional constellations for uplink SCMA systems – A comparative study", *IEEE Comm. Surveys & Tutorials*, vol. 21, no. 3, pp. 2169-2194, Thirdquarter 2019.

(Yang et al., 2019) P. Yang, Y. Xiao, M. Xiao, S. Li, "6G wireless communications: Vision and potential techniques," *IEEE Network*, vol. 33, no. 4, pp. 70-75, Jul./Aug. 2019.

(Zaman et al., 2018) M. Zaman, C.-H. Lung, "Evaluation of machine learning techniques for network intrusion detection," *IEEE/IFIP Network Operations and Management Symp.*, 2018.