Modular and Reconfigurable Testbed For 5G Systems And Applications

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Abstract—The fifth generation (5G) cellular standards operating in various millimeter frequency bands, are the proposed next telecommunications standards beyond the current 4G standards. The specifications of 5G technology are currently being standardized by international regulatory agencies and they hold promise for a wide array of applications ranging from transportation to health. Testing of this standard across a matrix of specifications and applications presents a daunting challenge. To overcome this, a 5G testbed design which is based on reconfigurable components enabled by Software Defined Networks (SDNs) and Software Defined Radios (SDRs) has been presented in this paper. The reconfigurable measurement hardware has been designed such that it can be integrated across all the layers of TCP/IP protocol through an open-source software defined architecture. Programmability is a key feature of this architecture, and this has been addressed by a Software Development Kit (SDK). The SDK contains pre-built IP, a baseline end to end stack implementation, and an application programming interface (API) for accessing different features of the platform. The testbed has been designed with a modular hardware and scalable software architecture so that it can facilitate the development of numerous 5G applications in the long run, allowing multiple users to operate it, thus making the testbed self-sustainable over the years.

Keywords–testbed; scalability; modular; 5G; health; transportation; energy.

I. INTRODUCTION

The fifth generation (5G) of cellular standards, holds promise for a variety of applications including, but not limited to, health, energy, transportation and public safety. 5G focuses on solving various present-day communication challenges, such as area traffic capacity, network energy efficiency, connection density and latency. It is being designed for enhanced mobile broadband applications such as streaming 4k video, augmented reality, and 3D gaming. Ultra reliable, low latency communication for autonomous driving and mission critical applications has been presented as an application area. 5G also is focused on improving spectrum efficiency and mobility, thus making it a prime candidate for massive machine to machine type applications such as in smart cities and smart factories.

While there is a lot of excitement around the promise that 5G holds, a key requirement is the need of common methodology and systems for testing these applications in real-world situations. It is extremely critical that researchers have a common test platform to validate scalability and interopertablity across these applications. 5G CHAMPION testbeds, described in [1], were designed for the 2018 Winter Olympic games, to validate how 5G-enabled mmWave wireless backhaul can provide an interoperable and seamless connection between two different access networks. 5G Hardware Test Evaluation Platform, presented in [2], deploys software defined wireless networks in the urban area, allowing academics, entrepreneurs and wireless companies to test, evaluate, and improve their hardware design and software algorithms in real-world environment. Additionally, it supports advanced wireless communications theory and technology research. An educational setup for service oriented process automation with 5G has been presented in [3]. The intended outcome is that students can obtain knowledge with emerging industrial technologies and become the actors of upcoming industrial revolution. A testbed described in [4] demonstrates SDN orchestration capabilities in adapting data paths across IoT, cloud, and network domains, based on the real-time load state of switches. This enables recovery from congestion, thereby assuring reliable data delivery services.

All of these testbeds have been designed to meet the requirements of a specific application or achieve a particular learning outcome. A key challenge is that these testbeds are not flexible to scale for different applications and evolving specifications. This paper presents a testbed architecture, based on reconfigurable Software Defined Networks (SDN) and Software Defined Radio (SDR) components. The testbed has been designed in a modular hardware fashion with a scalable software interface to allow its use for evolving 5G systems and technologies. It has been designed such that it can be integrated across all the layers of TCP/IP stack through an open-source software defined architecture containing a pre-built IP, a baseline end to end stack implementation, and an Application Programming Interface (API) for accessing different features of the platform. Section II describes the hardware architecture of the platform. Software architecture has been described in Section III. Sustainability aspects of the testbed have been described in Section IV. The testbed has been designed with the objective that it will facilitate the development of numerous 5G applications in the long run, some of which have been described in Section V.

II. HARDWARE ARCHITECTURE

The core of the testbed hardware lies in the SDR and SDN components that interface with other essential services such as data logging and aggregation access, administrative and performance monitoring services. They have been integrated in such a way that they can be controlled through a programming interface. This allows the testbed to interface with a variety of services frameworks. Figure 1 describes the overall architecture of the 5G testbed.

Flexibility at the baseband level is enabled via the use of SDRs such as USRP [5]. The current generation USRPs support 160MHz instantaneous bandwidth with frequency coverage from 10MHz to 6GHz, referred to as sub-6GHz in
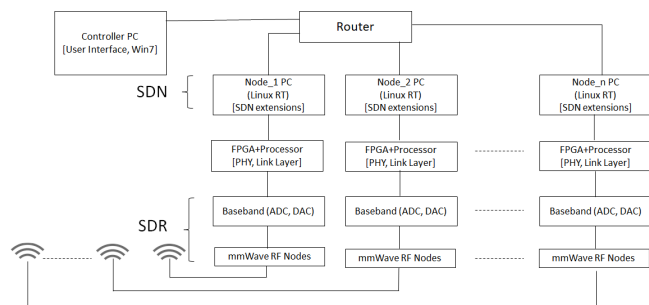
Figure 1. 5G Testbed Architecture

the rest of the paper. This serves as the baseband system of our testbed and provides sufficient frequency coverage and reconfigurability for research on topics such as Long Term Evolution (LTE)-to-5G migration, LTE-5G co-existence and/or convergence, and IoT. The modular nature of our testbed addresses one of the key 5G challenges related to the different frequency bands being considered [6], [7]. The World Radio Conference WRC-19 [8] and the designated ITU-R [9] qualifier for 5G, includes a set of bands to be considered for 5G, with direct applicability to 5G New Radio (5G NR). 5G NR is already taking shape in 3GPP with OFDM-based Unified Flexible Radio Access Technology below 40 GHz. Likewise, a non-stand-alone version was finalized in Dec. 2017 and several companies are releasing their 5G/KT mmWave spec. with a pre-standard for mmWave in 5G at 28 GHz for fixed wireless. As shown in Figure 2, the modular nature of the testbed allows the sub-6GHz system to be extended with mmWave up and down converters for different frequency bands. For example, a mmWave up/down converter for the 27.5-29.5 GHz band and direct interfaces to multi-element phased-array antenna RFICs have been added to the testbed. Some of the other spectrum bands which are under study for WRC-19 and can be added to the 5G testbed are the 37-40.5GHz 60-66GHz and 71-76GHz. To get to custom mmWave frequencies, RF daughter cards can be replaced by new commercially available upgrades or custom front ends. Local Oscillators (LO) can be used independently, in pairs or in external/shared modes.
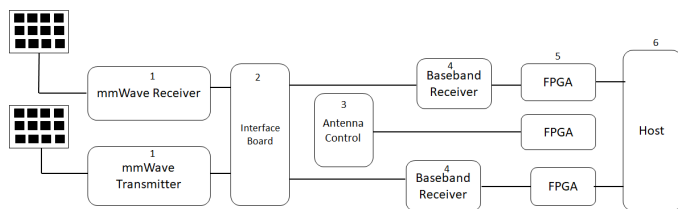

Figure 2. 5G Testbed Hardware Architecture

Earlier this year, ITU agreed on key 5G bandwidth requirements for IMT-2020 [10]; for example, the target values for downlink and uplink user experienced data rates were set at 100 Mbit/s and 50 Mbit/s respectively. These values are defined assuming supportable bandwidth as described in [11]; however, the bandwidth assumption does not form part of the requirement. Considering that the frequency and bandwidth requirements for 5G standards are still being defined and are in development, the 5G testbed described in this paper has been

designed in a modular fashion to adapt to different requirements. As Analog to Digital Conversion (ADC) technology evolves, we expect to see new digitizers with wider bandwidths to become commercially available. In the meantime, signal processing techniques such as spectrum stitching [12] can be used to achieve wider bandwidths by concatenating multiple USRPs. The RF interface block contains elements such as filters, amplifiers, switches and interfaces. Testbed has been designed to include multiple sub-6GHz RAN nodes, some of which can support indoor network research, while the rest can be located outdoors using roof mount and fixed ground installations.

Since directionality will be a key feature of 5G networks, beam forming and beam steering will be essential. Hybrid beamforming has been approved for LTE release 13, Phase 1. It has been shown that by significantly increasing the number of antennas, for example 64 antennas, the narrower beams can provide three to five times capacity gains, while taking advantage of existing infrastructure. For Phase 2 of LTE release 13, it is expected that each antenna will include its own transceiver, enabling both traditional MIMO techniques and the Zero Forcing beamforming approach, achieving 10 times capacity gain. To enable testing of this feature, an external phased-array antenna RFIC (such as SiBeam 12x12 element phased-array antenna) can be easily added to the 5G testbed. Many of the new 5G implementations will require beam steering on multiple beams. So, as advanced beam steering technology is developed and integrated into new 5G designs, the 5G testbed can be easily adapted using the Antenna Control block in Figure 2, to use 4 beams and 4 phased arrays for a total of 256 elements.

III. SOFTWARE ARCHITECTURE

Reconfigurability of the hardware elements is a key feature of the testbed and this is enabled by the control and processing software running either on the FPGAs or host computer. This section describes the software architecture of the 5G testbed, as shown in Figure 3. The testbed software has been designed using a plug and play architecture such that researchers can easily introduce new algorithms at any of the layers of the TCP/IP stack. It aims to provide users an insight into different blocks from an application point of view, without requiring them to go into any of the implementation details. Software will integrate the new algorithms, which can be deployed either on FPGA or host PC, with the rest of the stack and allow researchers to experiment with different settings. The testbed provides a default end-to-end stack, which will be used as a baseline. Users can then replace individual components in the stack. As an example, a researcher may like to develop a MaxWeight multiuser scheduler and then plug this algorithm at the MAC layer, without the need to know anything else about the baseline wireless stack. Once the user provides a binary representation of the new algorithm through a prescribed API, the platform will generate the entire stack, run the program, and provide throughput results. This will be based off the Key Performance Indicators (KPIs) which will indicate performance metrics, such as bandwidth, energy consumption, or latency.

The novel and guiding design principle of this testbed is rooted in its programmability across all layers, pre-built IP
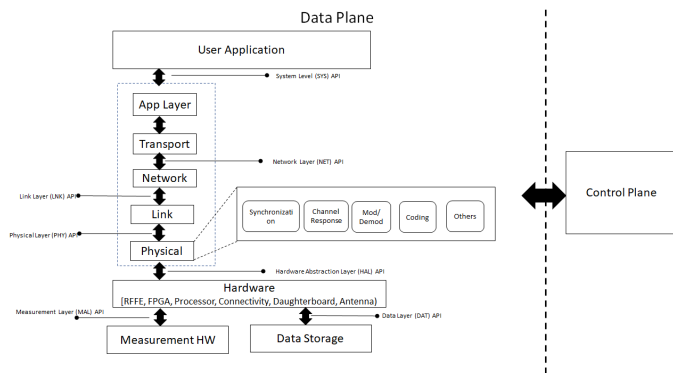
Figure 3. 5G Testbed Software Architecture

Figure 4. System Process for Usage Tracking and Billing

as a baseline implementation, and a hybrid approach to spectrum management that features both sub-6GHz and mmWave frequencies. This programmability has been provided through well defined interfaces such as NET API, PHY API, RF API, as shown in Figure 3 and described next.

SDN provides a breakthrough in network transformation. It decouples the software and the hardware layers by disengaging the data plane and control plane of the networking device [13]. Evolution of SDN programmability at network level will pave the way for new innovations. The testbed will leverage the principles of SDN to enable scalable, flexible and highly adaptive networking and communication layers through decoupling of the control and data planes. SDN will support efficient traffic and flow management, including resource reservations, and custom network layer protocols by abstracting the routing and networking intelligence (control layer) away from the switching hardware (data layer). The NET API will interface with the underlying radio signal processing plane abstractions using a well-defined API at each layer. It will be a superset of OpenFlow [14] and extensions for receiving information from different SDR blocks, such as modulators, coders, timing. It will also include a mechanism to define a set of actions for different network nodes. Users will be able to modify some contents of the packet, define performance indices, and deploy customized routing and switching protocols using this API. OpenFlow currently supports a limited number of protocols. This testbed will extend OpenFlow constructs for 4G and eventually 5G networks.

The PHY API is responsible for controlling the physical layer algorithm parameters such as modulation scheme, symbol rate, filter type, channel response equalization filter taps, coding parameters and such. This layer will also monitor the received signal characteristics such as RSSI and provide feedback to the upper layers. The testbed will be designed such that it allows for real-time configuration of RF layer parameters. The RF API will be responsible for controlling hardware specific parameters such as frequency, power level, and instantaneous bandwidth (specified as sampling rate). The RF API will abstract the features of the interface board to make it easier to program. Using General Purpose Input/Output (GPIO) lines on the USRP, the testbed will also facilitate real-time reconfiguration of RF hardware parameters using features such as Adaptive Gain Control (AGC).
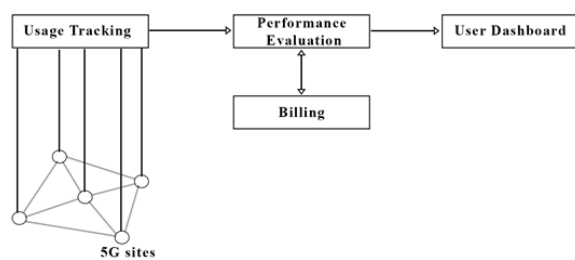
IV. USAGE TRACKING AND BILLING

Usage tracking and billing are important aspects for the successful implementation and monetization of the proposed 5G testbed. Usage tracking is crucial for the collection of raw experimental and platform utilization data whereas the billing mechanism provides the required monetization and the engagement of users. The proposed testbed will have a set of measurement instruments that will collect experimental and utilization data. The nature of the experimental data depends on the API layer that is used. For example, referring to Figure 3, measurements related to the testbeds Physical and Link layer API can be channel fading, time domain, frequency domain and modulation quality data. On the other hand, energy efficiency, throughput, latency and other measurements can be used for the characterization of the higher layers. Utilization data will keep track of the used platform resources of the experiment such as duration, number of APIs and 5G sites used and the overall energy consumption. The energy consumption provides information about the operational expenses of the platform for the purpose of the experiment but also can work as an incentive for researchers to design energy efficient 5G algorithms. This is because the billing will depend on the energy consumption.

In general, an important dimension of 5G networks is the energy efficiency [15] and different Key Performance Indicators (KPIs) have been proposed to quantify the efficiency [16]. An overlaid IoT based smart metering network capable of monitoring the energy consumption of the network will be used for energy monitoring. Each 5G site is expected to have at least 4 energy consumption points to capture the consumption at the radio unit, the IT equipment, the cooling/power units and of course the entire station to provide the required KPIs such as Joule/bps, W/m2, W/user, Power Usage Effectiveness (PUE). These measurements will also allow researchers to monitor and disaggregate the energy efficiency of the developed algorithms and create new energy efficiency proxies and metrics following recent advancements in the data center sector such as the Green Grid association [17].

Usage tracking data will be available to the researchers in real time during their experiments in a cloud based dashboard connected to the usage tracking database. A cloud platform interfacing the software and hardware of the 5G testbed will empower the users with the ability to remote access the system using time/frequency sharing scheduling processes.

The usage tracking data will be used to not only evaluate the efficiency of the experiments and the performance of the newly developed algorithms, but also to provide billing. The billing algorithm will use pricing principles met in Software

as a Service (SaaS) paradigms [18]. The pricing schemes can be based on an a-la-carte or a bundle approach providing the option to the end user to select according to the needs. The a-la-carte scheme allows a user to pay per experiment whereas the bundle approach creates packages of products, services and usage priorities with monthly subscription. For this case, the product is the API and the 5G site of the experiment and a user can select a number of them to be utilized for the experiment. The final cost of the pricing scheme is a function of the energy consumption, the number of 5G sites and APIs used and the performance of the algorithm. The overall process is presented in Figure 4.

V. APPLICATIONS

The 5G testbed has been designed with various general purpose wireless research and application specific research in mind, as shown in Figure 5. Understanding and defending against potential cyber-security attacks on SDNs, such as denial of service, is a key. The testbed can be used to test the self-evolving and self-healing characteristics of SDNs, taking inspiration from bio-inspired techniques. Some of the significant challenges that can be tackled through the testbed are the interference of small cells and macro-cells, new interference situations, and synchronization. Algorithms focusing on ultra-low latency (less than 10ms for remote medicine applications), ultra-high throughput (several Gbps for large scale data transfers) and support for massive number of devices (greater than 1000 for IoT applications). This testbed will allow for the fast reconfiguration of network nodes to handle a dynamic mix of such applications via selection of appropriate per-packet scheduling mechanisms. The testbed will also allow for sampling performance metrics such as latency, throughput, jitter, packet loss, and communicating these back to a central controller, which will use data-analytics to choose between a set of curated per-packet mechanisms to attain optimal system performance for the current applications.

Figure 5. 5G Applications

Some additional general purpose wireless research topics include analyzing new RF front end elements such as power amplifiers, filters and transceivers for mmWave, study of coexistence of sub-6GHz, 5G, and hybrid multi-spectral communication systems and the development of appropriate channel and fading models that are correlated to develop new systems concepts that can capitalize on spectral agility, new access schemes, and other resource management paradigms. While these are very important stand-alone research topics, they are particularly critical for many of the 5G application areas, as discussed next.
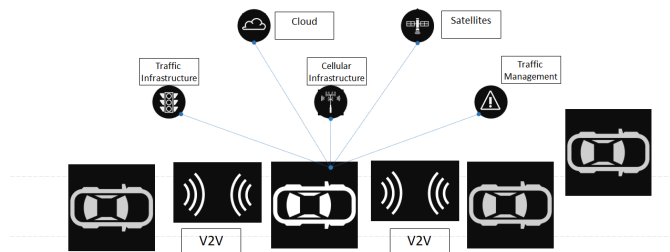
A. Transportation

Figure 6. 5G Applications for Transportation

Wireless communication is bringing a new level of connectivity to cars. As shown in Figure 6, with wireless, cars may communicate with each other directly in Vehicle-to-Vehicle (V2V) mode, or through the infrastructure in Vehicle-to-Infrastructure (V2I) mode. There are many applications of connectivity to support safety, transportation efficiency, and internet access. Additionally, connectivity makes self-driving cars safer by increasing their sensing range, leveraging what can be seen by other vehicles in the front, in the back, or on the sides. Exchanging such information between vehicles will improve driver assist and full automation over time. Unfortunately, conventional technologies such as dedicated short-range communications, which support data rates of megabits per-second and low-latency messaging, will not be sufficient to support the exchange of high rate sensor data or exchange of data to support automatic high definition map updates. 5G networks hold the promise to support high data rates and low latency for connected vehicles, which is driving tremendous interest in transportation as a key use case. In particular, mmWave 5G is especially attractive because of very high data rates, which can be used for the exchange of raw sensor data, enhancing the safety and efficiency of automotive driving. This would allow vehicles to enhance their situational awareness by seeing many car lengths in different directions, and around corners. Additionally, 5G can support lower latency and ultra-reliability to facilitate distributed control for transportation systems. For example, vehicles can travel together with smaller gaps using platooning, or can be coordinated through an intersection at high speeds without a traffic lights. These attributes enable safe operation of connected vehicles in a variety of traditional crash hot-spot situations such as overtaking on rural roads, conflicts at urban intersections, and weaving sections on highways. There are also opportunities to co-locate sensing and communication together in 5G systems. Sensing on the base station gives a birds-eye-view of the environment and may assist in automated intersection management. This functionality is supported by edge-computing, which will be supported by 5G networks.

B. Health

5G networks hold the possibility to empower new potential avenues regarding health care including imaging, diagnostics, data analytics, and treatment [13]. This includes devices such as clinical wearables, remote sensors and numerous different gadgets that screen and electronically transmit medical information such as vital signs, physical activity, individual security, and pharmaceutical adherence [19]. These devices will provide unprecedented telemedicine diagnosis and treatment benefits,

while significantly lowering health costs. These devices and capabilities generate higher fidelity data, thereby enabling precise analytics capabilities. For example, doctors typically require access to detailed information about hereditary, social condition, and way of life attributes to provide informed health care. The billions of devices and sensors connected through 5G will make collection of this information possible. Storing this information on a cloud infrastructure enables all-time accessibility. Some mission-critical medical functions require high dependability and accessibility with latency intervals that are down to a few milliseconds [20]. 5G will make this possible and predictable, thus enabling dependable client encounters to enhance medical care. Similarly, remote surgery will be possible once latency levels are reduced to small intervals. Surgeons will have the capacity to utilize virtual and augmented reality tools for certain kinds of techniques. Some other examples incorporate imaging, remote monitoring and diagnostics, and data analytics for effective treatment. Recently, wireless medical devices have enabled many hospital facilities the ability to provide continuous patient care throughout the treatment process. Standardization strategies to assist machine learning algorithms in adding to the efficiency of these devices would be the core interest. It will characterize the necessities of machine learning algorithms as they relate to network architectures and data security. Machine learning based data security will examine the information being transmitted between the patient and specialist to provide better treatment process. Utilizing the machine learning algorithms that iteratively learn from data, would enable these gadgets to discover hidden insights without being explicitly programmed to look for a specific pattern.

C. Energy

The energy sector is expected to be technologically enhanced with the direct, systematic and indirect implementations of 5G networks for energy-efficiency. The first pillar concerns the direct implementation of energy efficiency techniques in 5G access networks. By introducing new network planning and Base Station (BS) management strategies, the Joules required per offered bit will be reduced, integrating the 5G network into the paradigm of energy efficient networking, part of the ITU-R and IMT 2020 vision. 5G systems with high energy performance should be built on two design principles, a) to only be active and transmit when needed, b) to only be active and transmit where needed. The lean design architecture of 5G sites support sleep modes and the SDR capabilities enable BS on/off schemes. The most important challenges are resource allocation, resource sharing and base station management as well as integration of the latter with Renewable Energy Sources (RES). The deployment of a set of 5G off-grid sites powered by RES will provide an important testbed for experimentation and research. In the second pillar, the systematic application of 5G in the smart grid will enable a communication infrastructure which is able to support the emerging energy use-cases of 2020 and beyond. Part of the so-called Internet of energy, 5G networks support reliable data and command flow between a network of Internet of Things (IoT) such as smart meters/smart actuators and electric utilities. The third pillar concerns the indirect implementation of 5G networks to incorporate virtual spaces. This approach integrates densely-deployed IoT devices into an Augmented Reality (AR) environment for energy management. The main challenges concern the integration of high-rate, human-centric AR data with low-rate, machine-centric IoT data for effective cross-domain, real-time control. In addition, low latency end-to-end communications will be addressed, including applications of Ultra Reliable Low Latency Communications (URLLC). Such services are a key driver for the successful penetration of VR/AR services in 5G networks.

VI. CONCLUSION

Health, energy, public safety and transportation are some of the many applications that can benefit from 5G capabilities for latencies, massive bandwidth, and connectivity. 5G focuses on various aspects of present-day communication challenges such as area traffic capacity, network energy efficiency, connection density and latency. 5G also is focused on driving spectrum efficiency and mobility, thus making it a prime candidate for massive machine to machine type applications such as in smart cities and smart factories. This paper addresses a key gap in the long term adoption of this standard for these applications by presenting a modular and scalable testbed architecture to test interoperability and scalability of this standard across the various applications. For example, the ability of the testbed to adapt to various mmWave frequencies is crucial for self-driving cars as it has to work across the cellular, high bandwidth wireless (60G-66G) and evolving vehicular radar frequency bands (76G-82G). Likewise, the ability of the testbed to scale to multiple Transmit and Receive nodes is of big benefit for health applications. Ability to program at different layers is crucial to test machine learning enabled safety and security of 5G enabled wireless devices. Likewise, the ability to try different algorithms is of immense benefit to general purpose research and energy applications. In summary, we envision that this testbed will facilitate the development of numerous 5G applications in the long run. The testbed has some limitations which need to be addressed in future scope of work. For example, the USRP is currently not seen as a network interface card (NIC) by the operating system on the host machine. One needs to overcome this limitation by making the USRP visible as a virtual network interface. Once this is done, users can directly use the USRP to provide Internet connectivity via bridging it to an Ethernet NIC, and exploiting the existing TCP/IP stack on the host. Thus, using an Ethernet-Host-USRP combination as a fixed base station, with combinations such as USRP-Host-WiFi, USRP-Host-Bluetooth, and USRP-Host-Zigbee acting as client/mobile-access-points, connectivity to off-the-shelf handhelds and IoT devices will be possible, thereby enabling a new set of applications.

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