A prototyping methodology for SDN-controlled LTE using SDR

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Abstract

In this demo, we present a software and hardware platform for designing services in the next generation of wireless networks, in which SDN and SDR are expected to play a key role. We use a LabVIEW-based PXI platform in which LTE-like SISO OFDM PHY Layer is integrated with an open source protocol stack. Such platform can be easily used within an SDN framework to prototype PHY/MAC cross-layer algorithms as a solution to tame dense deployment of wireless networks. Furthermore, we present the preliminary integration of advanced PHY-MAC cross-layer algorithms for implementing novel schemes for future wireless networks.

I. INTRODUCTION

Mobile data traffic is growing exponentially and the trend is expected to continue for the next future, especially considering that 4G networks are becoming widely available and designing a fifth generation of mobile services and networks is already object of international research programs, such as the 5G PPP of the European Commission. At the same time, the requirements posed by new data-hungry and interactive applications for mobile devices create the need for a radical change in the architecture of cellular access networks. Indeed, local and incremental technology updates will not be able to keep pace with the growing and always-evolving traffic demand. In this context, the European Commission funded FP7 CROWD project[1] proposes the dense heterogeneous deployment of hierarchically controlled small cells, in addition to high power macro cells, as a potential solutions to satisfy users demand and their quality requirements. To achieve this goal, CROWD fosters the development of a control framework that leverages the Software Defined Networking (SDN) paradigm. In CROWD, it has been shown that the SDN-based approach can be suitably adopted to design the next generation of dense wireless mobile networks [1]. This approach enables the required level of flexibility and reconfigurability, while at the same time provides energy-efficient network infrastructure for both the radio access and the backhaul. Moreover, CROWD goes beyond SDN, since it enables the controller to process data flows. With the above, new control algorithms and applications trying to deal with complex interference issues or to optimize MAC operation need validation in a real-time testbed.

In particular, several algorithms for next generation systems have been proposed so to properly design and manage a denser access cellular network. The validation of above mentioned algorithms typically relies on simulations at PHY, MAC and higher layers and rarely the performance achieved are evaluated for the complete system in a realistic scenario. Indeed, the ever increasing complexity in all layers of current and future generations of cellular wireless systems has made an end-to-end demonstration of cellular networks limited to industrial research labs or large academic institutions. Possible commercial solutions are quite expensive to deploy and difficult to afford, as in case of MymoWireless [2] and Amarisoft [3]. An open source implementation of LTE eNB/UE stack is available within OpenAirInterface project.[2] However, it uses custom RF hardware for integration with base-band and is still in active development. As a result, researchers conduct simulations using tools like NS-3 and, once good results are achieved, they rewrite the algorithms in a totally different development environment for prototyping. This creates huge barriers both for testing algorithms in a real environment, and for evaluating the effects of new algorithms designed at the PHY/MAC layer on higher layers or vice versa.

The main motivation in our project is, therefore, to build a testbed that is cost-effective and that can easily interface with open source simulators like the NS-3 LENA LTE stack [4], allowing to create a unified platform for both simulations and prototyping. In particular, our prototyping platform uses NS-3 LTE LENA stack interfaced with a realistic subset of physical layer functions. In this regard, our demo shows how to make possible and affordable for universities and research centers to implement and demonstrate their proposals for cellular access networks using commercial-off-the-shelf hardware.

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[1] http://www.ict-crowd.eu

[2] http://www.openairinterface.org

Specifically, in this demo, we show how to use a LabVIEW[3]-based Software Defined Radio (SDR) testbed (for PHY layer and radio resource management) integrated with the open source NS-3 LENA LTE stack [4] (for MAC and higher layers). The resulting testbed allows for a realistic implementation of the key parts of the LTE stack. In particular, we use a LabVIEW-based PXI platform, whose graphical interface allows very efficient and fast prototyping, providing a common development environment for all the heterogeneous elements in the SDR system with tight hardware/software integration and a good abstraction layer. The platform is able to run in real-time and allows fast development and validation for a broad set of novel mechanisms. Nevertheless, the main goal of the testbed is to create a small-cell dense LTE network that can be used, e.g., to evaluate the performance of enhanced Inter-cell Interference Coordination (eICIC) algorithms, such as those defined for the Almost Blank Subframe (ABS) mechanism [5].

The organization of paper is as follows. Section II introduces the basics of CROWD Architecture. This is followed by Section III, which describes the general architecture of the testbed. In Section IV we describe a few important use cases that we aim to demonstrate with our testbed. Finally, we conclude the paper with Section V that describes next steps and future direction.

II. CROWD ARCHITECTURE

The proposed CROWD architecture [1] aims at leveraging the heterogeneity of dense wireless deployments, both in terms of radio condition and non-homogeneous technologies. It offers tools to orchestrate the network elements to mitigate intra-system interference, improve performance of channel-opportunistic transmission/reception techniques, and reduce energy consumption. An extremely dense and heterogeneous network deployment comprises two domains of physical network elements: backhaul and Radio Access Network (RAN). The latter is expected to become increasingly heterogeneous not only in terms of technologies (e.g., 3G, LTE, WiFi) and cell ranges (e.g., macro-/pico-/femto-cells), but also at density levels (e.g., from macro-cell Base-Station (BS) coverage in underpopulated areas to several tens or hundreds of potentially reachable BSs in hot spots). Such heterogeneity also creates high traffic variability over time due to statistical multiplexing, mobility of users, and variable-rate applications. In order to achieve optimal performance most of the times, reconfiguration of the network element is required at different time intervals from very fast (few 10s of milliseconds) to relatively long (few hours), affecting the design of backhaul and the RAN components. In order to tackle the complex problem of reconfiguration, we propose to follow an SDN-based approach for the management of network elements as shown in Fig. 1. Network optimisation in the proposed architecture is assigned to a set of *controllers*, which are virtual entities deployed dynamically over the physical devices. These controllers are technology-agnostic and vendor-independent, which allow full exploitation of the diversity of deployment/equipment characteristics. They expose a *northbound interface*, which is an open Application Program Interface (API) to the *control applications*. We define *control applications* as the algorithm that actually performs the optimization of network elements, for example ABS. The *northbound interface* does not need be concerned with either the details of the data acquisition from the network or the enforcement of decisions. Instead, a *southbound interface* is responsible for managing the interaction between controllers and network elements.

We propose two types of controllers in the network (see Fig. 1): the CROWD Regional Controller (CRC), which is a logical centralized entity that executes long-term optimisations, and the CROWD Local Controller (CLC), which runs short-term optimizations. The CRC only requires aggregate data from the network, and is in charge of the dynamic deployment and life cycle management of the CLC. The CLC requires data from the network at a more granular time scale. For this reason, CLC only covers a limited number of BSs [1]. The CLC can be hosted by a backhaul/RAN node itself, e.g., a macro-cell BS, so as to keep the optimisation intelligence close to the network. On the other hand, the CRC is likely to run on dedicated hardware in network operator data centre. Such an SDN-based architecture allows the freedom to run many *control applications* which can fine tune the network operation with different optimization criteria, e.g., capacity, energy efficiency, etc. The CROWD vision aims to provide a common set of functions as part of *southbound interface* which can be used by the *control applications*, for example *LTE access selection* [6] and *LTE interference mitigation* [7] to configure network elements of a dense deployment.

III. TESTBED ARCHITECTURE

In out testbed, we try to ensure that essential LTE Physical layer features are standard compliant or at least that the behavior is close to LTE philosophy. In this way, researchers can focus more on the performance of algorithmic aspects rather than the implementation details of the algorithm within LTE standard in a realistic testbed. In particular, we show preliminary integration results on how an LTE based PHY layer interfaces with the open source NS-3 LTE LENA stack [4]. We also propose an initial concept on how this testbed can be used to demonstrate eICIC algorithm, for example ABS [5], along with several other use cases which will be fine-tuned using SDN-based approach in the later stage of the project.

In order to interface NS-3 LTE LENA stack with a realistic Physical layer and be able to run the testbed in real-time, we implemented specific physical layer control/data channels (PDCCH/PDSCH) in FPGA/DSP or similar high-performance computing platform. However, writing physical layer code in Verilog/VHDL can be quite daunting and interfacing the base-band with RF Front-end has its own set of challenges. Hence, we chose LabVIEW as the SDR platform. LabVIEW platform is PXI-based and is a very powerful and feature-rich rapid prototyping tool [8] for research in real-time wireless communication systems. This SDR platform provides a rich heterogeneous environment including multi-core Windows/Linux PC and real-time

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[3] LabVIEW is graphical system design tool for prototyping and is a trademark of National Instruments Corp.

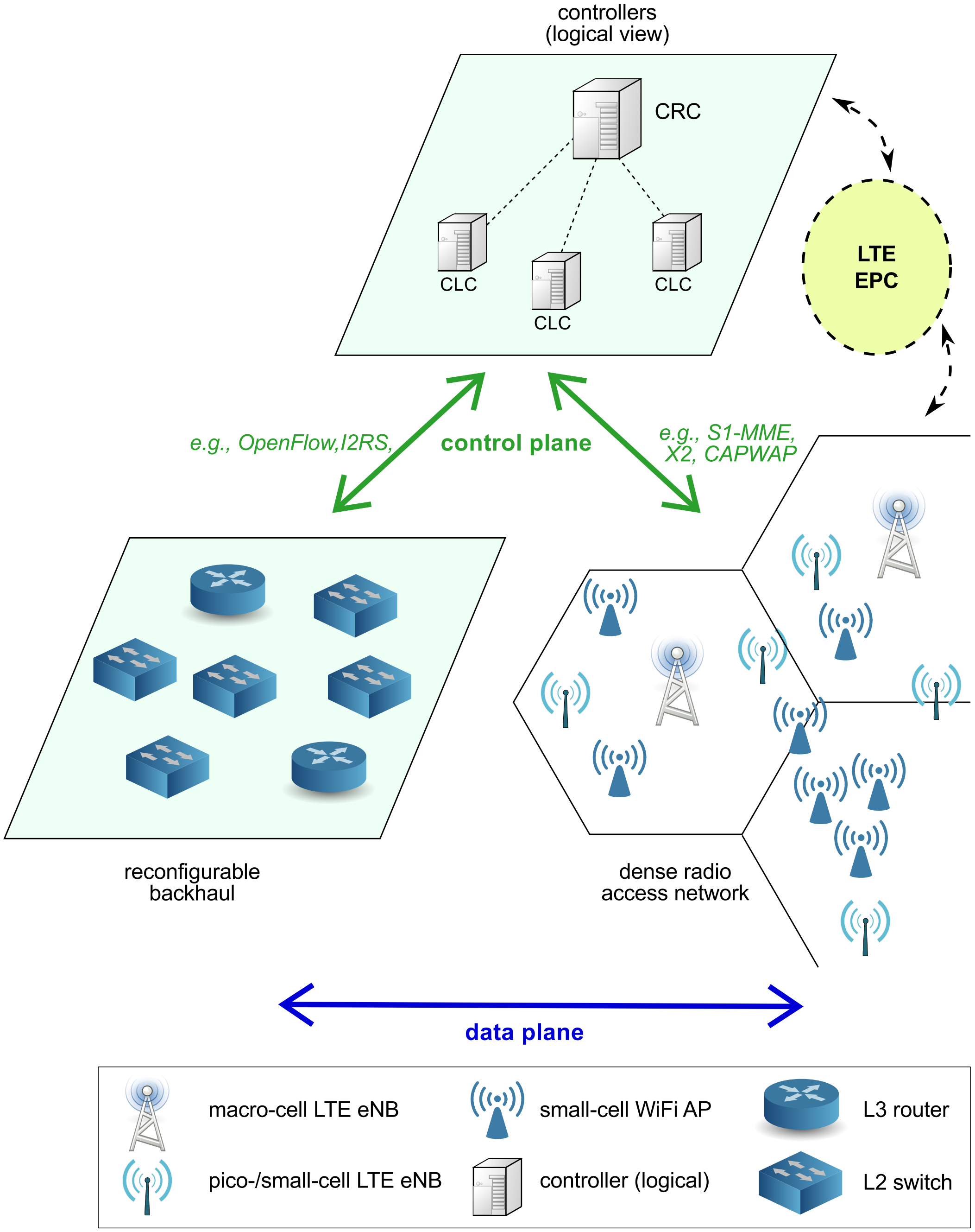

Fig. 1: Network control architecture.

operating system (RTOS) running on high-performance general purpose processors (GPP) such as Intel processors and FlexRIO FPGA modules containing Xilinx Virtex-5 and Kintex-7 FPGAs. It also provides a rich set of RF, Digital to Analog Converter (DAC) and Analog to Digital Converter (ADC) modules that can meet the bandwidth and signal quality requirements of 5G systems.

Traditional SDR prototyping engineer faces several challenges which arise due to the use of different software design flows to address different components of the system (i.e., RF, baseband, and protocol stack). In addition, the components may lack a common abstraction layer. This can result in complications and delays during system development and integration. The NI LabVIEW graphical system design software is able instead to address these challenges by providing a common development environment for all the heterogeneous elements in the NI SDR system (i.e., the GPP, RTOS, FPGA, converters and RF components), with tight hardware/software integration and a good abstraction layer [9]. This integrated design environment enabled us to quickly reach an initial working version of our demonstration system and it is the primary reason we chose the LabVIEW SDR platform. LabVIEW significantly eases the physical layer design using graphical system design tool (LabVIEW FPGA) and, thanks to the PXI platform, it allowed to have preliminary proof-of-concept demo interfacing NS-3 LENA LTE

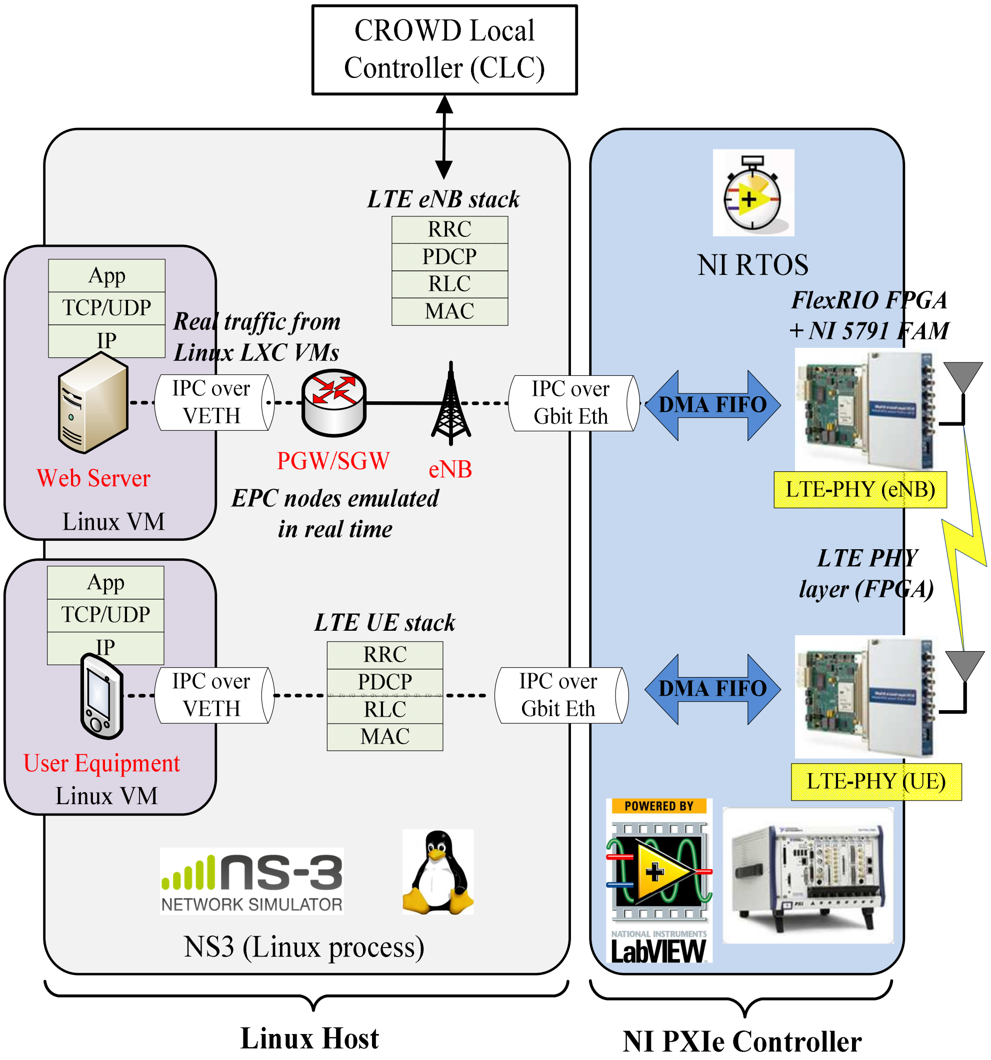

Fig. 2: Testbed architecture.

stack with LabVIEW Physical layer [10], [11] in a matter of months.

Fig. 2 shows the general overview of testbed architecture. The functions of the MAC and higher-layer protocols (including the SDN-like CROWD Local Controller) run on a Linux computer. The protocol stack communicates with PHY layer running on NI/PXI system over Ethernet using an L1-L2 API that is based on Small Cell Forum API [12]. We have implemented the complex high throughput baseband signal processing for an "LTE-like" OFDM transceiver for the eNB and UE in LabVIEW FPGA using several FlexRIO FPGA modules due to the high throughput requirements. We use NI 5791 FlexRIO Adapter Module (FAM) as RF transceiver. This module has continuous frequency coverage from 200 MHz to 4.4 GHz and 100 MHz of instantaneous bandwidth on both TX and RX chains. It features a single-stage, direct conversion architecture, providing high bandwidth in the small form factor of an NI FAM.

A. Introduction to LabVIEW based LTE-like PHY

The current PHY implementation has only one antenna port (i.e., SISO) supported per node with FDD operation. We have chosen to implement only the downlink transmitter/receiver and we plan to show the performance of our algorithms in downlink direction. The PHY modules have been designed to loosely follow 3GPP specifications, and hence referred to as "LTE-like" system, since our testbed is intended for research instead of commercial development. We describe main LTE OFDMA downlink system parameters in Table I. However, some components and procedures of a commercial LTE transceiver (for example, random access and broadcast channel) have deliberately been omitted because they fall outside the scope and requirements of our testbed. Only essential data and control channel functions are implemented.

We use Xilinx Coregen library for the channel coding, FFT/IFFT and filter blocks, while custom algorithms have been developed in LabVIEW for all the other blocks. On the transmitter side (see Fig. 3), Physical Downlink Shared Channel (PDSCH)

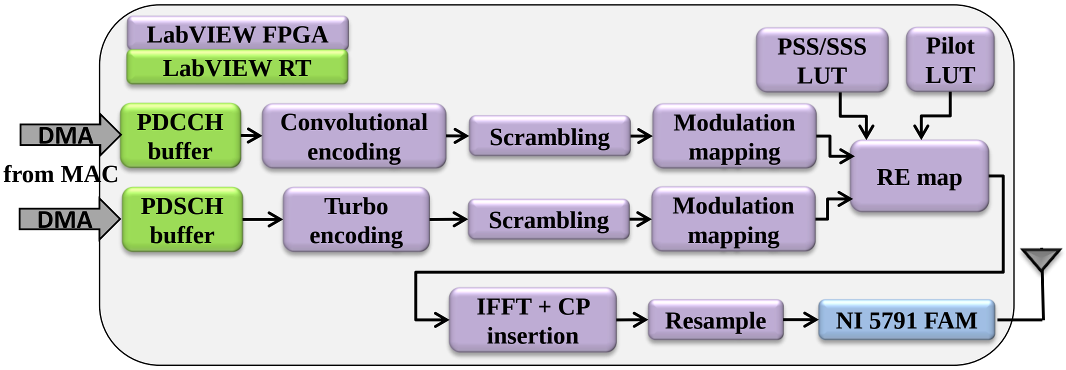

Fig. 3: LTE-DL transmitter FPGA block diagram.

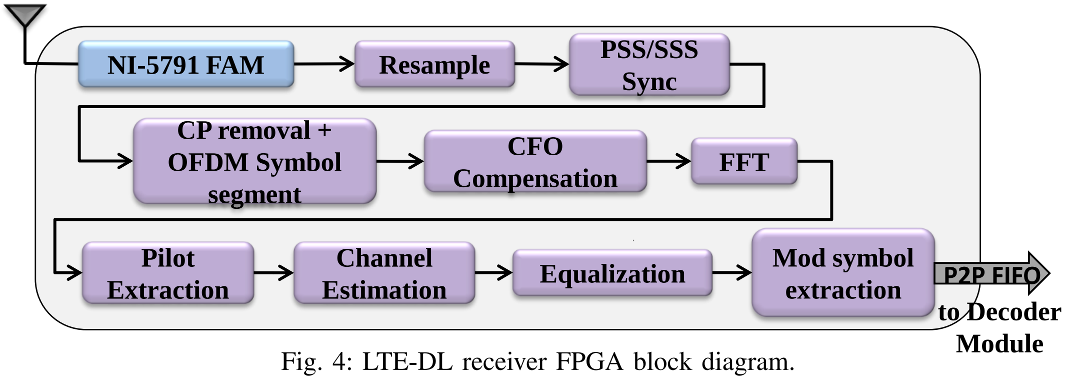

Fig. 4: LTE-DL receiver FPGA block diagram.

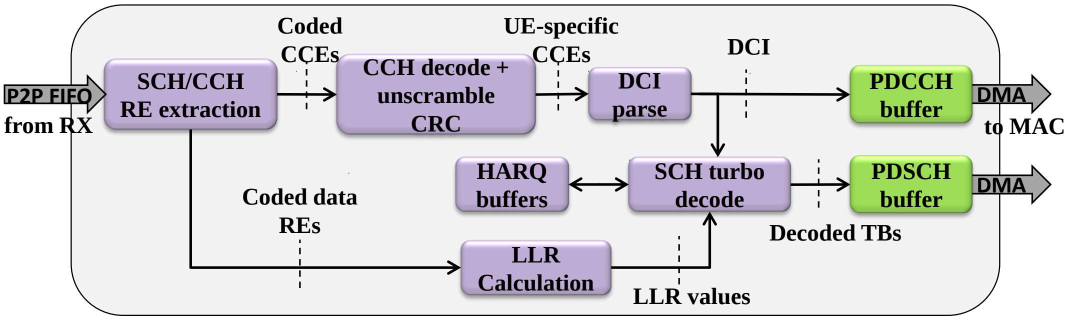

Fig. 5: LTE-DL PDCCH and PDSCH decoder FPGA block diagram.

TABLE I: LTE-like OFDM system parameters

Parameter	**Value**
Sub-carrier Spacing (Δf)	15 kHz
FFT Size (N)	2048
Cyclic Prefix (CP) length (N_g)	512 samples
Sampling frequency (F_s)	30.72 MS/s
Bandwidth	1.4, 3, 5, 10, 15, 20 MHz
Number of used sub-carriers	72,180,300,600,900,1200
Pilots/Reference Symbols (RS) spacing	Uniform (6 sub-carriers)

and Physical Downlink Control Channel (PDCCH) Transport Blocks (TB) are transferred from the MAC layer and processed by each subsystem block as they are synchronously streamed through the system. Handshaking and synchronization logic between each subsystem coordinate each module's operations on the stream of data. The fields of the Downlink Control Information (DCI), including parameters specifying the Modulation and Coding Scheme (MCS) and Resource Block (RB) mapping, are generated by the MAC layer and provided to the respective blocks for controlling the data channel processing. Once the PDCCH and PDSCH data are appropriately encoded, scrambled and modulated, they are fed to the Resource Element (RE) mapper to be multiplexed with RSs and Primary and Secondary Synchronization Sequences (PSS/SSS), which are stored in static look-up tables on the FPGA. Presently, the RB pattern is fixed and supports only one user. However, multi-user and dynamic resource allocation will be included in later versions. OFDM symbols are generated as shown in Fig. 3 and converted to analog for transmission over-the-air by the NI 5791 RF transceiver.

Fig. 4 shows the high-level block diagram of our OFDM receiver implementation. The NI 5791 RF transceiver receives the analog signal and converts it to digital samples for processing by the FPGA. This is followed by time synchronization based on the LTE PSS/SSS. The cyclic prefix (CP) is then removed, OFDM symbols are segmented out and the Carrier Frequency Offset (CFO) Compensation module corrects for CFO impairments. Fast-Fourier Transform (FFT) is then performed on the samples and reference symbols are extracted for channel estimation and equalization. The equalized modulation symbols for the data and control channels are then fed to a separate decoder FPGA, which is connected to the receiver FPGA using a Peer-to-Peer (P2P) stream over the PCI Express backplane of the PXI chassis. Fig. 5 shows the implementation of the downlink channel decoder. The first stage of the decoding process is to demultiplex the symbols belonging to the PDSCH and PDCCH. The DCI is then decoded from the PDCCH Control Channel Elements (CCEs) and passed to the SCH turbo decoder module to decode the PDSCH data, which are finally sent to the MAC using the Small Cell Forum API [12].

B. Introduction to Open Source NS-3 LENA LTE Stack

We have adopted the NS-3 LTE LENA simulator/emulator [4] as the framework for implementing the upper-layer LTE stack for our testbed platform. We leverage the protocols and procedures provided in the robust LTE LENA model library, which are generally compliant with 3GPP standards. Fairly complete implementations of the data-plane MAC, RLC, and PDCP protocols are provided along with simplified versions of the control-plane RRC and S1-AP protocols. Some core network protocols such as GTP-U/GTP-C and the S1 interface are partially implemented as well. Though used primarily by researchers as a discrete-event network simulator, NS-3 can also be configured to function as a real-time network emulator and interfaced with external hardware. By creating instances of LTE nodes on top of the NS-3 real-time scheduler, we can effectively emulate the LTE eNB and UE stack. Also, by utilizing the provided Message Passing Interface (MPI) support, we can exploit parallelism to boost the performance of NS-3. By running each node instance in a separate thread or process, we can conceivably emulate multiple eNB, UE and core network nodes all on the same multi-core host, as represented in Fig. 2.

IV. USE CASES

In this section, we describe few important use cases that we aim to demonstrate using the proposed testbed architecture. The use cases below serve as a guiding principle for the MAC/PHY architecture and in future we plan to further develop the proposed HW/SW architecture to serve the needs of these use cases. We believe these use cases are fundamental to solving the spectral/energy efficiency, dense networks architectural challenges for the next generation wireless networks.

A. LTE ICIC/eICIC Algorithms

A major drawback of the LTE multi-cellular system is inter-cell interference due the fact that it uses frequency reuse 1 to maximize spectral efficiency. The impact of this interference is quite detrimental to especially cell edge users. The problem of inter-cell interference is even worse with macro, micro and pico cell deployments. Traffic channels in LTE can sustain BLER of 10%, however control channels cannot. In order to address this problem, 3GPP introduced Inter-cell Interference Coordination (ICIC) algorithm that mitigates interference on traffic channels. There are several different variants of ICIC described below:

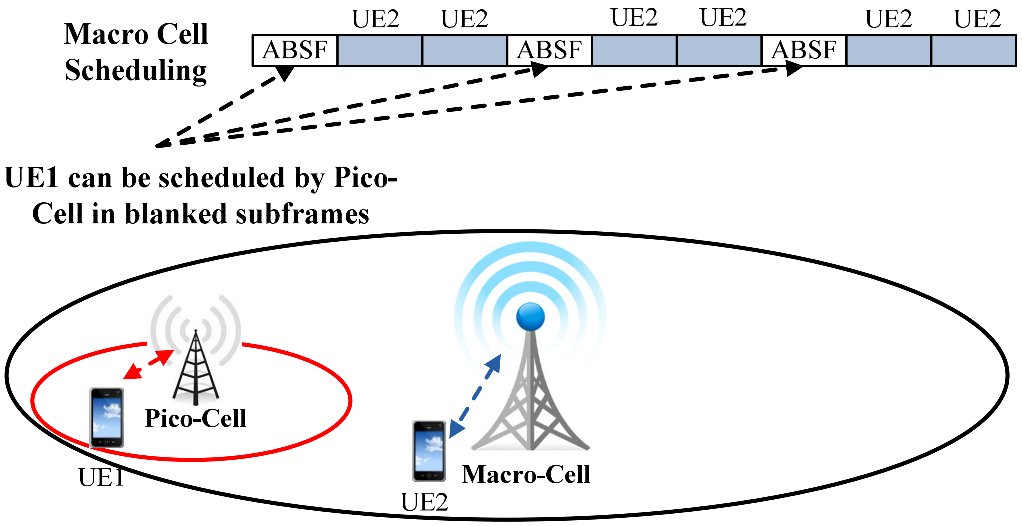

Fig. 6: Almost Blank Sub-Frame (ABS) overview.

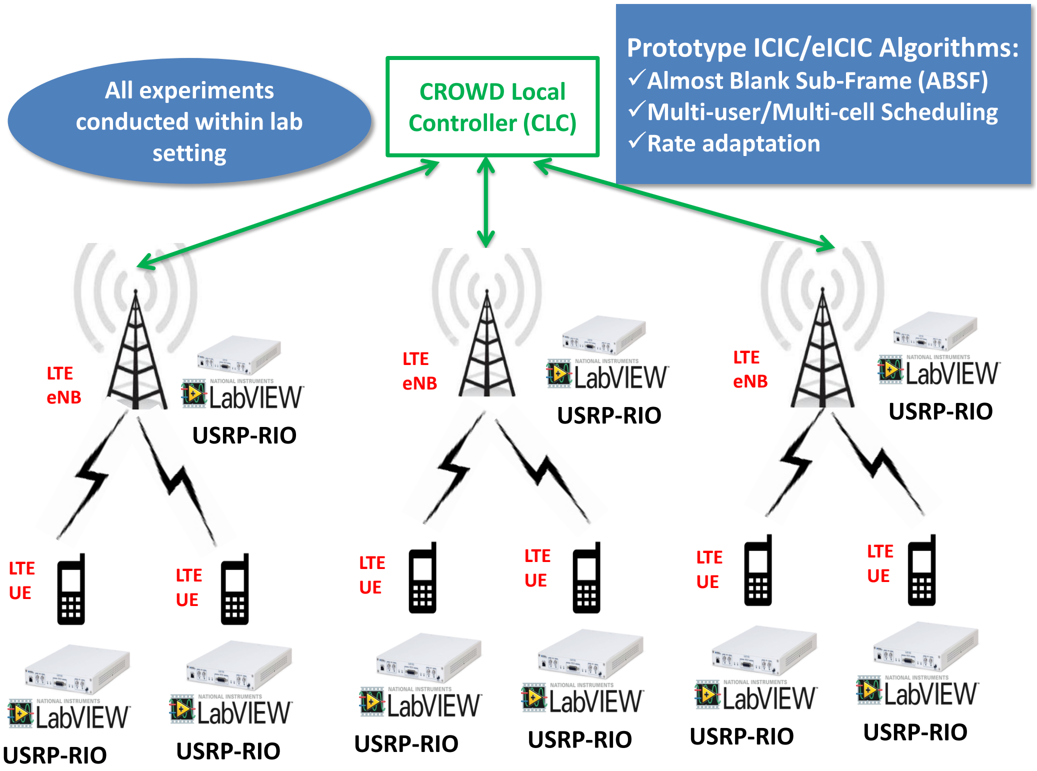

Fig. 7: LTE eICIC/ICIC Prototyping.

- Neighbor eNBs use different sets of resource blocks throughout the cell at given time, i.e., no two neighbor eNBs will use same resource assignments for their UEs. This greatly improves cell-edge SINR. The disadvantage is the decrease in throughput throughout the cell, since full resources blocks are not being utilized.
- All eNBs utilize complete range of resource blocks for centrally located users but for cell-edge users, no two neighbor eNBs use the same set of resource blocks at give time.
- All the neighbor eNBs use different power schemes across the spectrum while resource block assignment can be according to the second scheme explained above. For example, eNB can use power boost for cell edge users with specific set of resources (not used by neighbors), while keeping low signal power for center users having available all resource blocks.

ICIC relies on information sharing between eNBs via X2 interface. In CROWD project, we propose the eNBs share information with CROWD Local Controller (CLC), which in turns influences the base-station scheduling to apply specific ICIC mechanism. In our testbed, we can easily exchange information about BS (eNB) scheduling over X2 interface (that runs over Ethernet) to CLC, which then instructs a particular ICIC scheme. The current PHY layer implementation along with MAC/PHY interface is capable, with few planned updates, of performing multi-user scheduling along with different power allocations for different Resource Blocks.

3GPP further introduced Enhanced Inter-cell interference coordination (eICIC) release 10 to deal with issues of interference in Heterogeneous Networks (HetNet). eICIC allows mitigation of interference on traffic and control channels using power, frequency and time-domain coordinated scheduling of multiple BSs. eICIC introduces the concept of ABS. ABS [13], as shown in Fig. 6, mitigates the inter-cell interference by assigning resources such that some base stations produce blank subframes, thus preventing their activity when the interference exceeds a threshold. Several centralized and distributed solutions have been already suggested in the literature to exploit the ABS mechanism. Our proposal is designed to be implemented in the CLC, which is in charge of acquiring the user channel conditions and computing an optimal base station scheduling pattern in the available subframes using SDN framework. Fig. 7 shows the architecture of CROWD testbed to implement ABS algorithm.

B. LTE/WiFi Coexistence

The deployment of modern wireless communication system faces severe challenges due to spectrum scarcity. In order to address this problem, there have been proposals to offload LTE traffic on WiFi networks or vice versa. There have also been proposals from 3GPP and other companies [14]–[17] to propose the usage of LTE in unlicensed bands. While this requires modifications to LTE standard, the open architecture of our LTE framework allows to conduct such experiments and easily

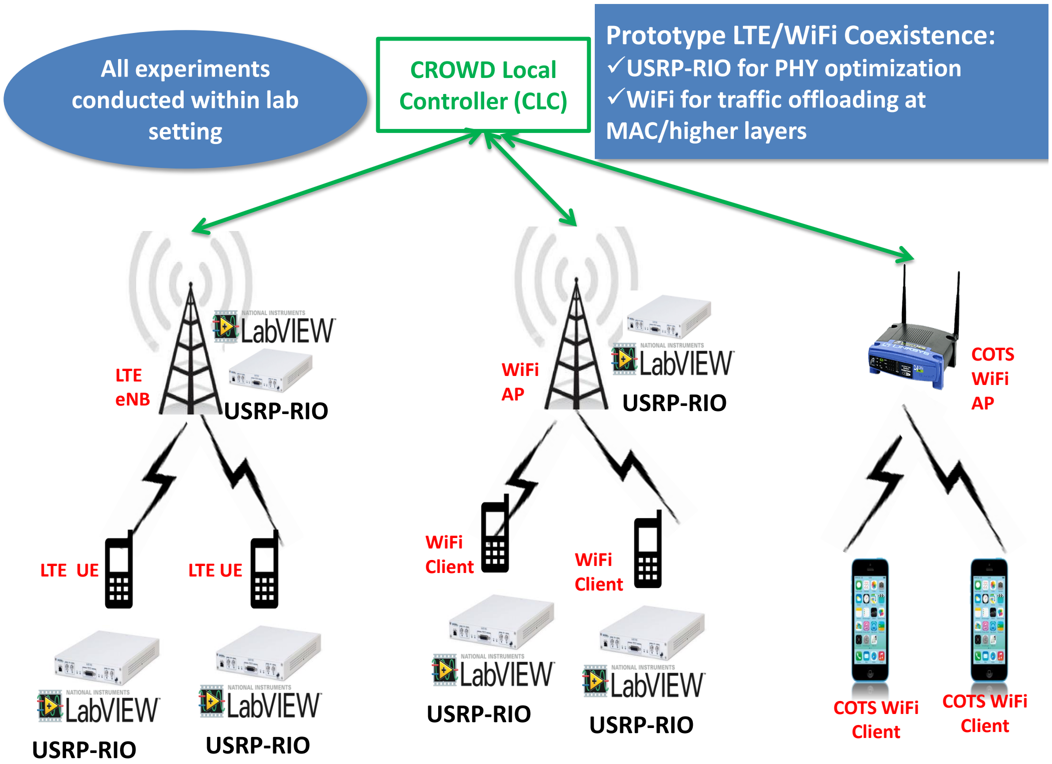

Fig. 8: LTE/WiFi Coexistence Prototyping.

modify the current physical layer design. As a first step, we plan to integrate LTE testbed with existing WiFi testbed to offload LTE traffic to WiFi network coordinated by CLC. In future, we plan to extend MAC/PHY framework to include features like sense and transmit within the API to enable study of coexistence algorithms. Fig. 8 shows the architecture of LTE/WiFi Coexistence prototyping within CROWD testbed.

C. LTE Device-to-Device (D2D) Communication

D2D communications in LTE (also known as LTE Direct) is an emerging paradigm that enables direct communication among cellular devices by bypassing the eNB (see Fig. 9). This paradigm is a key factor in proximity-aware services and allows for more efficient device discovery procedure and higher communication speed. Moreover, the network-assisted nature of LTE Direct circumvents the existing concerns regarding security, privacy, and energy consumption. In particular, inheriting the existing LTE features, which are highly optimized in terms of latency and energy efficiency, and incorporating them into the framework of LTE Direct results in drastic performance enhancement in comparison to the existing approaches such as Over-The-Top that uses GPS, or Bluetooth Low Energy and WiFi Direct. 3GPP is already considering to incorporate this technology in Release-12 [18] as public safety feature. Fig. 9 shows the overall system architecture for prototyping LTE D2D algorithms in CROWD testbed.

D. Cloud Radio Access Network (C-RAN)

Cloud RAN (C-RAN) [19] is an emerging architecture of RAN which proposed to change the traditional distributed RAN architecture. The basic idea behind C-RAN is to change the traditional RAN architecture so that it can take advantage of technologies like cloud computing, SDN approaches, and advanced remote antenna/radio head techniques. C-RAN is a RAN architecture that is not bound to a single RAN air interface technology. In essence, conventional terrestrial cell site base stations are replaced with remote clusters of centralized virtual base stations which can support up to a hundred remote radio/antenna units. This is achieved by centralizing RAN functionality into a shared resource pool or cloud (the digital unit, or baseband unit) which is then connected via fibre to advanced remote radio heads (Radio Units, RRH) sited in different geographical locations in order to provide full coverage of an area.

Centralized base-band pool processing, Co-operative radio with distributed antenna equipped by RRHs and real-time C-RAN can address the challenges the operators are faced with and meet the requirements. Centralized signal processing greatly reduces the number of site's equipment room needed to cover the same areas. Co-operative radio with distributed antennas equipped by RRHs provides higher spectrum efficiency. Real-time Cloud infrastructure based on open platform and BS virtualization enables processing aggregation and dynamic allocation, reducing the power consumption and increasing the infrastructure utilization

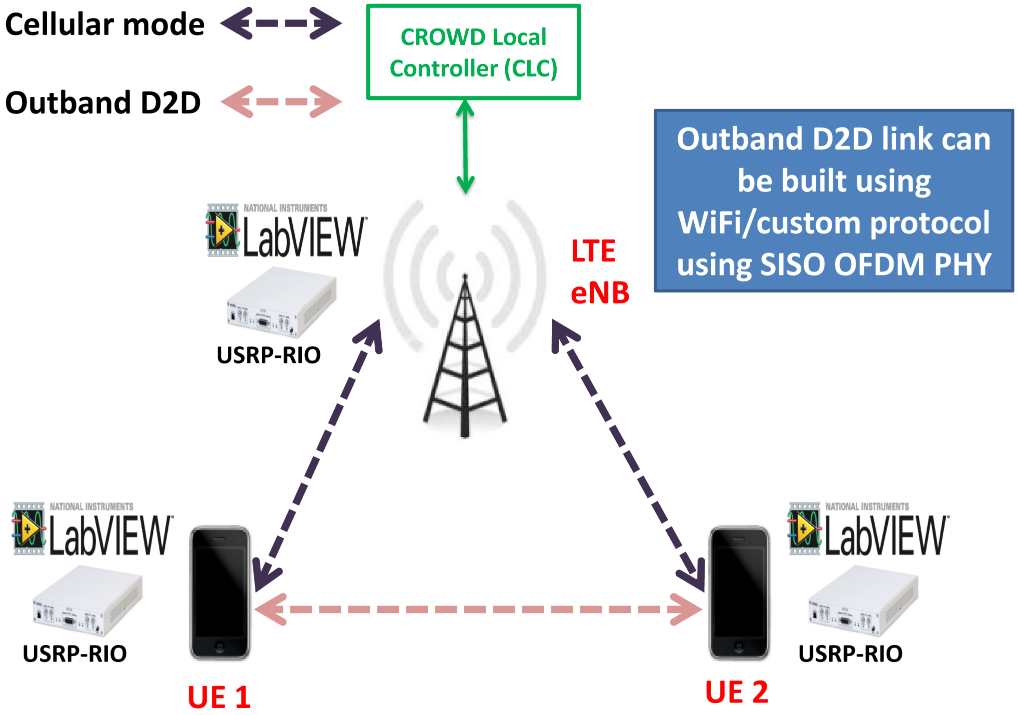

Fig. 9: LTE-Direct Prototyping.

rate. These novel technologies provide an innovative approach to enabling the operators to not only meet the requirements but advance the network to provide coverage, new services, and lower support costs. Fig. 10 shows the example architecture for C-RAN prototyping using CROWD testbed.

V. CONCLUSION

In this paper, we showed how the NI/PXI platform based on LabVIEW can be used for advanced wireless LTE prototyping to demonstrate end-to-end link. Since the design of the testbed is based on open source protocol stack and modular hardware from NI PXI Platform, it is much more cost effective compared to other commercial LTE testbed solutions, especially for demonstrating research ideas for next generation wireless systems. The graphical system design based on LabVIEW and its integrated environment were ones of the key enablers to achieve significant results and make good progress with testbed integration. The next step is to complete the implementation of PDCCH and also the implementation of small cell forum API, so as to allow full integration of LTE PHY layer with NS-3 in real-time. In the end, we aim to demonstrate the performance of our proposed algorithms in a lab setting using multiple cells emulated on several PXI systems, in many of the use cases presented in Section IV.

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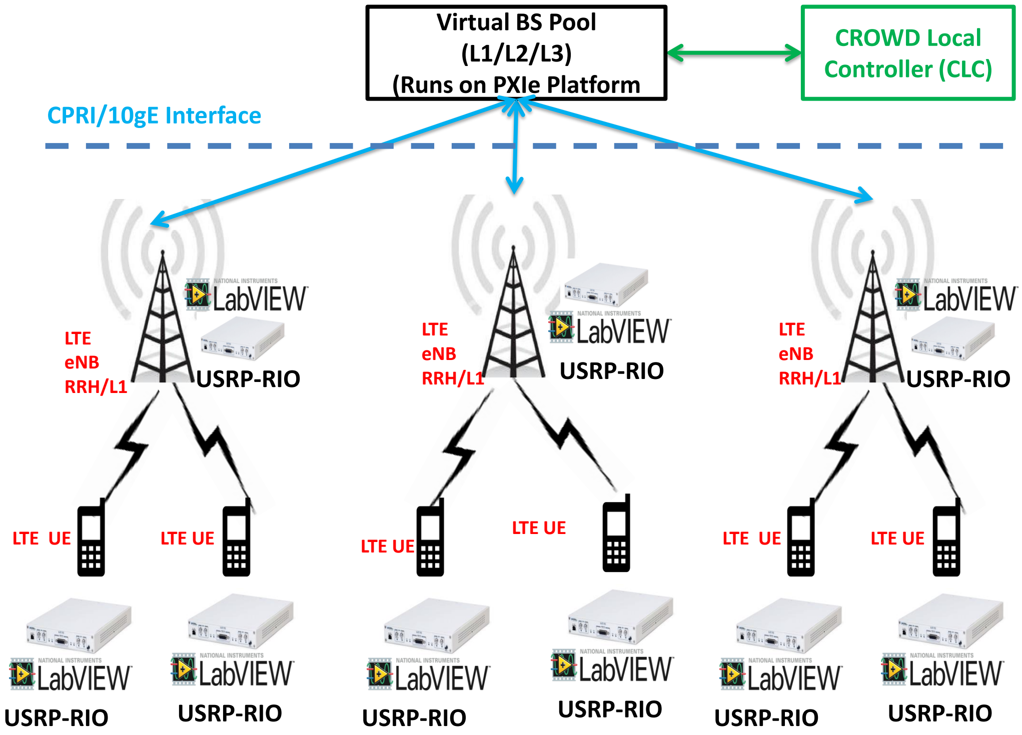

Fig. 10: Cloud RAN (C-RAN) Prototyping.

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