LABVIEW BASED SOFTWARE-DEFINED PHYSICAL/MAC LAYER ARCHITECTURE FOR PROTOTYPING DENSE LTE NETWORKS

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ABSTRACT

We propose to adopt and extend the Software Defined Networking (SDN) paradigm to manage interference within dense heterogeneous deployments of wireless network cells. Specifically, we present a network architecture and the initial research results we have achieved by using software-defined physical and MAC layers to build a small scale LTE testbed. To build the testbed presented in this paper, we have used LabVIEW and the open-source NS-3 LENA LTE stack for real time emulation of dense deployments. The testbed has been designed to serve as a powerful validation and demonstration tool for algorithms proposed within the framework of the CROWD project for tackling the challenges of dense and heterogeneous wireless deployments.[1] Our testbed specifically allows to study the performance of cross layer PHY/MAC control algorithms within a realistic cellular environment.

1 INTRODUCTION

Mobile data traffic demand is growing exponentially and the trend is expected to continue for the near future, especially with the deployment of 5G networks. In order to cope with such rapid explosion of traffic demand, mobile network operators have already started to push for denser, heterogeneous deployments. However, interference due to uncoordinated resource sharing techniques represents a key limiting factor in the design of dense wireless networks, where resources are limited due to either the costs for licensed bands or the proliferation of hot spots in license-exempt bands.

This situation calls for the deployment of agile *network controllers*, with the aim of orchestrating the utilization of wireless and backhaul resources, to achieve efficiency in both resource utilization and energy consumption. Indeed, in the FP7 CROWD project [1] we have shown how a Software-Defined Networking (SDN) based approach can be suitably adopted to design the next generation of dense wireless mobile networks. The CROWD approach is based on a two-tier control architecture of *local* or *regional* controllers, which enables the required level of flexibility and reconfigurability, while at the same time providing energy-efficient network infrastructure for both the radio access and the backhaul. However, to demonstrate and validate, in a realistic framework, architectural and algorithmic solutions such as the ones proposed in CROWD, it is needed to design and deploy SDN prototypes that tackle the challenges of dense and heterogeneous wireless deployments. Moreover, to be able to implement novel and flexible network control functions in real wireless devices, the prototyping has to involve Software Defined Radio (SDR) techniques.

SDN/SDR prototyping is quite challenging as it demands high degree of flexibility at all layers of protocol stack [2]. As a first step, it is required to build a general purpose API especially for PHY/MAC layers which can allow SDN Controllers [3] to externally control the parameters at run-time. This problem becomes even more challenging as current/future communication systems are experiencing high throughput while at the same time imposing low-latency requirements. Another very important aspect of SDN/SDR prototyping platform is to be able to create a library of basic building blocks on which new configurations of future communication systems can be experimented. SDR platform also has to be able to scale elegantly for large bandwidths/antenna configurations thus requiring a scalable platform which has elegant combination of General Purpose Processor (GPP)/FPGA interconnected with very high-speed and low la-

[1]CROWD (Connectivity management for eneRgy Optimised Wireless Dense networks) is a research project funded by the European Commission in the Seventh Framework Programme.

tency backplane which can be scaled up/down depending on the compute needs of the communication system.

There have been quite a few SDR platforms around, see GnuRadio [4], BEECube [5], Nutaq [6] and SORA [7]. However, we chose LabVIEW due to its integrated graphical system design and ability to integrate PHY/MAC designs within a single environment, with the possibility to develop suitable APIs for SDN control applications. LabVIEW can be run seamlessly on GPPs to write MAC/Higher layers, while at the same time can be used to build high throughput/low latency signal processing blocks for physical layer. LabVIEW seamlessly runs on a wide range of high-end PXI [8] based products that can meet the needs of large processing capabilities, and can also be simultaneously deployed towards USRP based products [9], which are more compact and cost-effective. LabVIEW allows the same source code to transition efficiently towards both the hardware targets (PXI and USRP) to meet communication needs of the researcher, thus allowing end end user to scale the system for wide-variety of applications.

As concerns LTE experimental platforms, there are already existing LTE designs [10, 11], but we chose to implement basic building blocks in LabVIEW so we could incorporate configurability/modifiability aspects into the design at an early stage. LTE standard is much more complex compared to WiFi, and minor changes in for instance physical layer can lead to incompatibilities at higher layers and vice versa. Hence, we based our design on LTE parameters but implemented only a subset considering the behavior we want to investigate, which is primarily focused on creating dense LTE-like environment and studying the interference-limited scenarios within a lab environment. The main motivation of this paper is to evaluate the architecture of general purpose LTE-like general purpose physical layer written in LabVIEW which is intuitively modifiable due to the graphical design environment offered by LabVIEW. The design also hides the RF/Inter-FPGA/FPGA-Host Communication thus allowing a researcher to focus on the algorithm rather than the complex and demanding integration aspects of SDR prototyping. The current paper builds on our earlier work [12], in which we presented overall system architecture to build LTE testbed using SISO OFDM Physical Layer written in LabVIEW and NS-3 LENA stack [13].

The main contribution of this paper is to describe the design of physical layer architecture and illustrate the configurable/modifiable aspects of our approach. We build on our previous work [12] and give an overview of the L1-L2 API, which allows interfacing the physical layer with external protocol stacks. We also illustrate use cases of dense small cell prototyping, which can be emulated over such a testbed. Some of these use cases are being studied both experimentally and theoretically within the context of CROWD project. Finally, we present initial results for rate-adaptation/multi-user scheduling which serve as a building block to conduct future experiments to explore the design space for SDN.

The paper is organized as follows. Section 2 introduces the

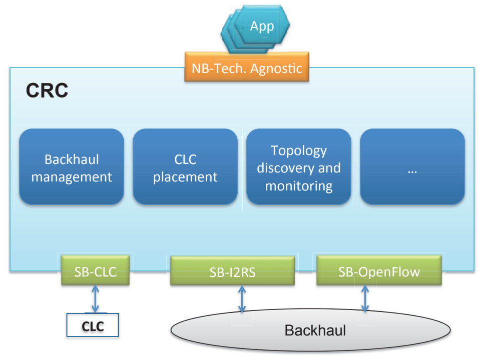


Figure 1: CROWD Regional Controller.

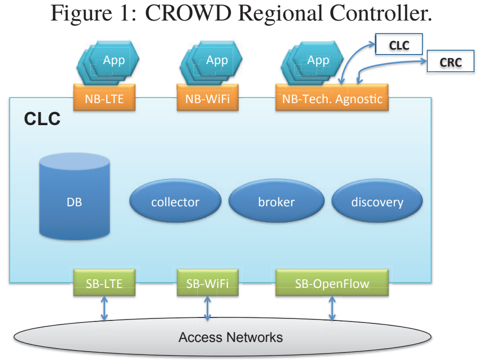


Figure 2: CROWD Local Controller.

CROWD architecture that serves as the basis for our work. We also highlight in this section how we plan to integrate CROWD SDN controllers into our PHY/MAC framework. Section 3 introduces the high level API messages that enables software-defined aspects of the proposed physical layer and lends itself to be programmable through SDN controllers via higher layers of LTE protocol stack. Section 4 describes the implementation aspects of high throughput LTE Downlink PHY layer that also has building blocks to implement LTE Uplink. Section 5 describes the use cases that we plan to target to demonstrate the SDN concepts within the framework of CROWD project. Section 6 describes initial results for physical layer calibration and initial experiments that we have conducted in the lab settings. Finally, we conclude the paper with future work and next steps in section 7.

2 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 access (often referred to as RAN—Radio Access Network). The latter is expected to become increasingly heterogeneous not only in terms of technologies (e.g., 3G, LTE, WiFi), 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 BS in hot spots). Such heterogeneity also creates high traffic variability over time due to statistical multiplexing, mobility of users, and variable-rate applications. In the following, we first give a brief overview of the CROWD control architecture; subsequently we dig into the control of LTE eNBs, with focus on real implementation of both network controllers and controllable-devices for LTE.

2.1 A two-tier control architecture

In order to achieve optimal performance most of the times, reconfiguration of the network element is required at different time scales, from very short intervals (few tens of milliseconds) to relatively long periods (few hours), affecting the design of backhaul and 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 Figs. 1 and 2. Network optimisation in the proposed architecture is assigned to a set of *controllers*, which are virtual entities deployed dynamically over the physical devices to control the activity of a group of close-by cells on short time scales (CLC—CROWD Local Controller) or the activity of several groups of cells at macro level at medium/long time scales (CRC—CROWD Regional Controller). These controllers are technology-agnostic and vendor-independent, which allow full exploitation of the diversity of deployment/equipment characteristics. Controllers expose a *northbound interface*, which is an open Application Program Interface (API) to the *control applications*. We define *control application* as the algorithm that actually performs the optimization of network elements, for example the control algorithm for driving Almost Blank Sub-Frame (ABSF) decisions [14]. 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. Fig. 1 shows the architecture of a CRC and its interfaces towards control applications and network elements, for instance towards other controllers (via a CLC-specific southbound interface), routers (via OpenFlow), and switches (via IR2S) present in the backhaul. At the local level, CLC shown in Fig. 2 is responsible for the direct control of network elements in the access network via tech-specific southbound interfaces (e.g., LTE eNBs, WiFi devices, etc.).

2.2 Controlling the LTE eNB

In Fig. 3, we illustrate in more detail how proposed SDN controllers (i.e., CLCs, in this specific case) interact with LTE MAC/PHY interface of an LTE eNB to collect statistics regarding link performance in terms of throughput, channel state information, etc., while at the same time proposing eNB behavioral

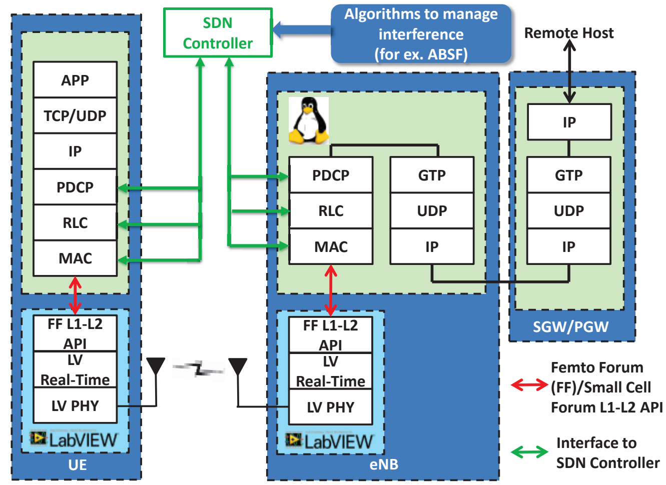


Figure 3: LTE MAC/PHY SDN Architecture for CLC controlling eNBs.

changes via a controller-MAC Scheduler API. In general, a CLC controller interacts with the MAC layer of eNBs to influence parameters related to scheduling; however, this interface can be easily extended to higher layer of protocol stack. It should also be noted that CLC interfaces can be also be extended to interface with UE protocol stack, however this results in the usage of LTE air interface for interaction of SDN Controller/UE protocol stack and the benefits of such SDN application scenarios should be carefully investigated. In general, the currently implemented CROWD architecture allows SDN controllers to interact only with eNBs and not UEs, so as to minimize changes to UE standards. However, we have proposed a general-purpose architecture that could enable future use cases in which SDN controllers interacts with both eNB and UE.

To enable flexible utilization of LTE PHY and resource allocation mechanisms, we could not rely on commercial devices, since they do not come with standard APIs that would allow access to the eNB scheduler and protocols, and so enable dynamic reconfiguration of the eNB. Instead, we have implemented a general-purpose PHY/MAC interface using Small-Cell Forum L1-L2 API [15], and we have deployed the fundamental LTE PHY and resource allocation schemes in FPGA, using LabVIEW-based NI PXI platform. The L1-L2 API allows integration of the standard LTE protocol stack with the proposed PHY/MAC architecture. The specifications of API and their important features are described in Section 3.

We do not intend to introduce in the paper the details regarding the controller-MAC Scheduler API, whereas in what follows we will focus on the MAC-PHY API. In light of above discussion, such API is key to enable more flexibly the use cases that arise out of SDN-based deployments.

3 GENERALIZED LTE MAC/PHY INTERFACE ARCHITECTURE

In this section, we describe the generalized LTE MAC/PHY interface architecture. Since, we are developing the LTE MAC/PHY interface for prototyping both eNB/UE, it is important that we exploit commonalities in such interface. In this paper, we focus more on downlink MAC/PHY interface, however, we plan to extend this description to include uplink as well. We also point out the commonalities/differences between UL/DL MAC/PHY interface for eNB/UE. Fig. 3 illustrates the positioning of MAC/PHY interface within the overall architecture. We describe the list of important messages that are exchanged between MAC/PHY interface of eNB/UE to allow closed-loop interaction between eNB/UE. We have used Small Cell Forum eNB L1-L2 API [15] as a basis for designing our API, while proposing extensions for allowing the usage for this API at the UE side as well. It should be noted here that the goal of our testbed is for research purposes only to allow flexibility and ease of use for researchers to integrate their algorithms into our testbed. It is in this context that we have made simplifications to the API and even extended it to accommodate more generalized MAC/PHY Architecture for eNB/UE Uplink and Downlink control/data channels. The LTE standard as a whole is quite complex and it is prohibitive to implement all the features and scenarios for both eNB/UE. Hence, we focus on specific use cases described in Section 5 to allow for experimentation of scenarios for dense small cells prototyping within an indoor lab setting along with usage of SDN Controllers, for example CROWD Local Controller (CLC) or some other distributed/centralized approaches for managing such interference. The API description below should be interpreted in this regard and not with respect to strictly implementing LTE standard to fulfill the requirements for the commercial end-products.

1. **PHY_CONFIG_REQ**: This message is sent once per initialization from MAC to PHY and configures the following parameters of the eNB physical layer (cell ID, RF Frequency, cell bandwidth, MIMO Configuration). In the case of UE, the UE configures its DL PHY interface to the above parameters to allow synchronization to specific (cell ID, RF Frequency, cell bandwidth, MIMO Configuration). This results in avoidance of complex cell search at the UE side, while at the same time, allows the creation of interference-limited environment within indoor lab setting by configuring different eNB-UE pairs with different cell IDs/RF Frequencies. The configuration of cell-ID implies specific Primary Synchronization Sequence (PSS), Secondary Synchronization Sequence (SSS), Reference Symbol (RS) location and sequence, thus allowing eNB/UE to synchronize to each other and create a cell. The uplink parameters in this message are initialized in direct relation to downlink parameters.

2. **START_PHY_REQ**: This message starts the PHY layer and is always sent by the MAC layer.

3. **STOP_PHY_REQ**: This message stops the PHY layer and is always sent by the MAC layer.

4. **RESET_FRAME_REQ**: This message is sent by the protocol stack of eNB/UE to reset the system frame counter of the PHY. This message is sent once after initialization of protocol stack to synchronize MAC/PHY modules. We assume in our testbed that MAC layer is the master of the PHY.

5. **SUBFRAME_IND**: This message is sent by the PHY to MAC interface every TTI (1ms), and contains current system frame/subframe number to enable continuous synchronization between PHY/MAC modules. This message allows the corresponding PHY/MAC modules to correct the time drift which occurs due to the fact that PHY layer is implemented in FPGA, whereas MAC layer resides on General Purpose Processor (GPP), each having their own clock drift. Each subframe indication message for the UE also contains the SINR of received PSS/SSS Synchronization signal, which is then passed to higher layers with MAC/PHY API to allow for the serving cell measurements.

6. **TX_REQ**: This message is used by the eNB/UE protocol stack to pass MAC Control/Data PDUs to the PHY layer for transmission. In case of eNB, it contains a list of DCI (Downlink Control Information) message that carry scheduling information along with associated MAC PDUs. In case of UE, it contains the UCI (Uplink Control Information) message along with associated MAC payload.

7. **RX_IND**: This message is sent by the PHY to eNB/UE protocol stack and indicates the received PHY Control Channels and MAC PDUs. It also contains the SINR of received packet.

8. **MEAS_CONFIG_REQ**: This message instructs the PHY to synchronize to neighboring cells and make measurements. The PHY layer is stopped during this procedure. The message contains following parameters: start/end duration of measurement, cell ID, center frequency, bandwidth and MIMO configuration. These parameters are enough to make the necessary neighboring cell RSSI/RSRP/RSRQ measurements. Such measurements are the key enabler for Enhanced Inter-Cell Interference Coordination (eICIC) algorithms [16].

9. **MEAS_REPORT_IND**: This message is sent by the PHY to the MAC layer as a results of status report indication in response to neighboring cell measurements made by **MEAS_CONFIG_REQ**. This message is then passed onto the higher layer, for example scheduler via MAC/PHY API for further processing and enabling the eICIC algorithms.

10. **SRS_CONFIG_REQ**: This message sent by UE MAC to PHY interface to enable Sounding Reference Signal (SRS) configuration that is used to measure uplink signal quality from the users within a cell.

11. **SRS_REPORT_IND**: This message is sent by the eNB PHY to MAC layer and contains the SRS reports containing uplink measurements.

12. **ENABLE_SYNCHRONIZATION_REQ**: This message is used to synchronize multiple eNB protocol stacks. This message allows synchronized execution of protocol stacks thus allowing synchronization at the granularity of TTI (1ms) at the MAC layer. This feature is one of the key enablers for eICIC algorithms which require multi-eNB synchronization, for example ABS. Such synchronization can be achieved using NI-TimeSynch module [17], which can be configured to use either IEEE 1588 PtP protocol [18] that runs over Ethernet or using GPS as the external clock source. The methods mentioned above achieve different levels of synchronization, however the requirement for synchronization at the PHY layer requires that different downlink signals arrive within cyclic prefix duration, which is 4.7 us for normal duration and 16 us for extended duration. Since, the uplink is always synchronized to the downlink signal, this automatically results in the synchronization of uplink signal as well.

13. **DL_POWER_CONFIG_REQ**: This message is sent from eNB MAC to PHY to configure the power of Reference Symbols (RS), PSS, SSS, Control/Data channels, thus allowing different power levels neighboring cells to create/reduce neighboring cell interference.

14. **UL_POWER_CONFIG_REQ**: This message is sent from UE MAC to PHY to configure the UE transmit power for uplink transport channels.

4 PHY IMPLEMENTATION

This section gives a brief overview of the functional partitioning into LabVIEW real-time host code and LabVIEW (LV) FPGA code as shown in Fig. 4. The transmitter (TX) part is split into a host application and one FPGA board. The receiver (RX) is utilizing two FPGA boards, one for the base-band processing and the other one for decoding the data, and a host application as well. The communication between the LV real-time application (host) and the FPGA board (target) is done by using LV elements, called host-to-target (H2T) and target-to-host (T2H) FIFOs. For the inter-FPGA communication, we use peer-to-peer (P2P) FIFOs.

4.1 Transmitter design

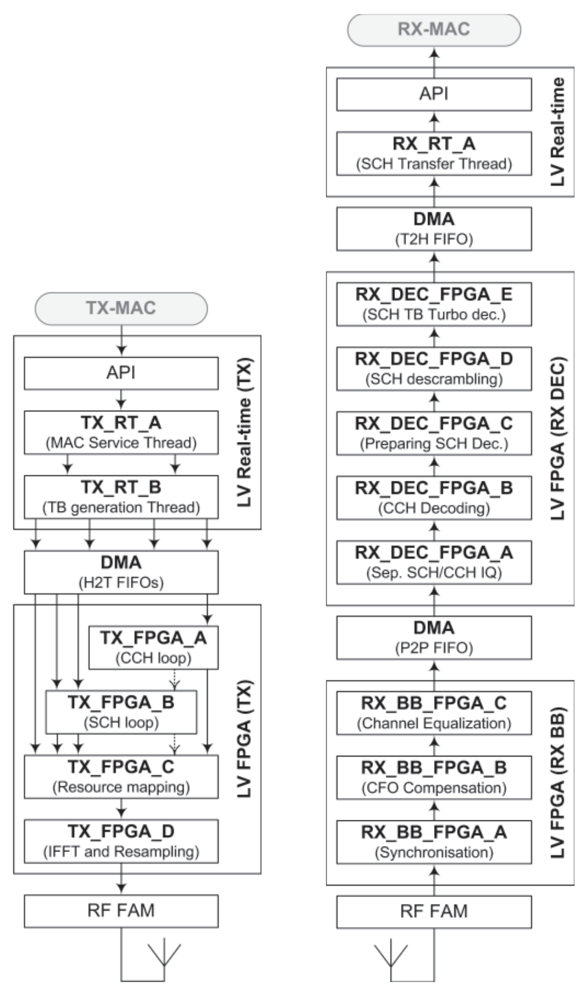
The overview of transmitter design is shown in Fig. 4(a). A detailed view of the TX RT Host implementation is shown in Fig. 5, and the detailed view of TX FPGA implementation is shown in Fig. 6.

4.1.1 TX_RT_A - MAC Service Thread

This thread receives UDP packets with the L1-L2 API messages from the MAC layer and parses them. According to the content of those UDP packets the Control Channel (CCH) and Shared Channel Transport Block (SCH TB) queues are filled.

4.1.2 TX_RT_B - TB Generation Thread

This thread runs every millisecond and is triggered by the indication of TX FPGA. The Thread is reading from the queues filled by the MAC Service request. After reading the data from the CCH queue the DCI message is built and written to the DCI MSG H2T FIFO. The Xilinx channel encoder parameters are calculated and written to the SCH Encoder H2T FIFO. The resource mapper configuration is generated and written to the Resource map H2T FIFO. This thread also transfers the SCH TB



(a) Transmitter (b) Receiver

Figure 4: Overview of the PHY Architecture

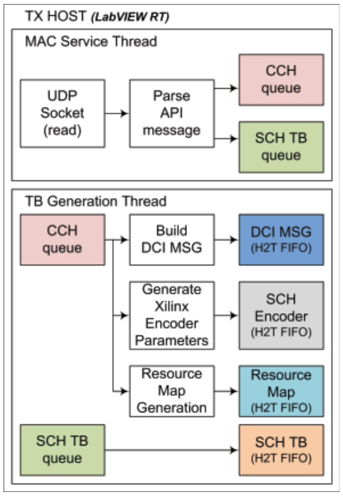


Figure 5: Detailed view of TX Host Architecture

data from the SCH TB queue (RT) to the H2T FIFO as well.

4.1.3 TX_FPGA_A - CCH loop

The DCI message is read from the DCI MSG H2T FIFO and fed to a Xilinx convolution encoder. Afterward, the data is interleaved and QPSK mapped. Finally, the mapped data is written to the CCH IQ FIFO.

4.1.4 TX_FPGA_B - SCH loop

The parameters for the Xilinx LTE DL Channel encoder are read from SCH Encoder H2T FIFO. This data configures the Encoder and after the configuration the SCH TB H2T FIFO is read and the data is fed to the Encoder. The setup and data transfer to the Encoder is controlled by the SCH Encoder FSM. The encoded data is now scrambled with the "Gold Code" followed by QAM mapping. The mapped data is then sent to the appropriate UE SCH IQ queue. The code scrambling and QAM mapping is controlled by the *Scrambling Modulation FSM*.

4.1.5 TX_FPGA_C - Resource mapping

The module maps the different IQ data according to the resource map.

4.1.6 TX_FPGA_D - IFFT and resampling

Here the TX IQ data is fed to the IFFT and afterwards resampled to the DAC rate of the RF FAM module.

4.2 Receiver design

The receiver design, as shown in Fig. 4(b), is explained in the following subsection in more detail. A detailed view of RX baseband FPGA implementation is shown in Fig. 7. The detailed view of RX decoder FPGA implementation is illustrated in Fig. 8. Finally the details of the RX RT Host implementation are shown in Fig. 5.

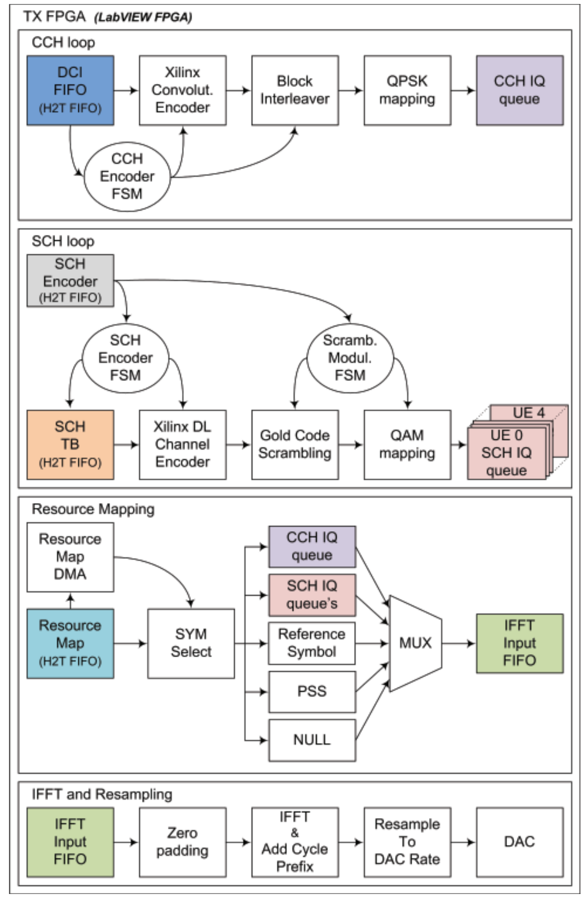


Figure 6: Detailed view of TX FPGA Architecture

4.2.1 RX_BB_FPGA_A - Synchronization

The received IQ data is fed through a Low pass filter and decimate block. This signal goes to a Correlator bank and afterwards there is the PSS peak detection. This information is then used to update the timing offset for the synchronization.

4.2.2 RX_BB_FPGA_B - CFO Compensation

The received IQ data if fed trough another Low Pass Decimate block to estimate the CFO (Carrier Frequency Offset) phase. The segmented OFDM symbols are now compensated with this estimated value.

4.2.3 RX_BB_FPGA_C - Channel Equalization

The segmented OFDM symbol are then passed through FFT, and then the pilots are extracted, the channel is estimated and the data is compensated by the Channel estimation values. The result is stored in a Peer-to-Peer (P2P) FIFO and transferred to the RX Decoder FPGA.

4.2.4 RX_DEC_FPGA_A - Separate SCH and CCH IQ data

The incoming IQ data from the base-band FPGA will now be separated into CCH, 1st OFDM symbol data, and SCH data, remaining 11 OFDM symbols.

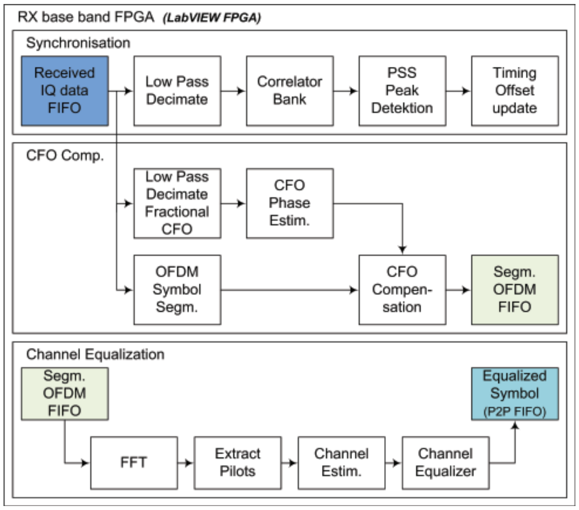


Figure 7: Detailed view of RX base-band FPGA Architecture

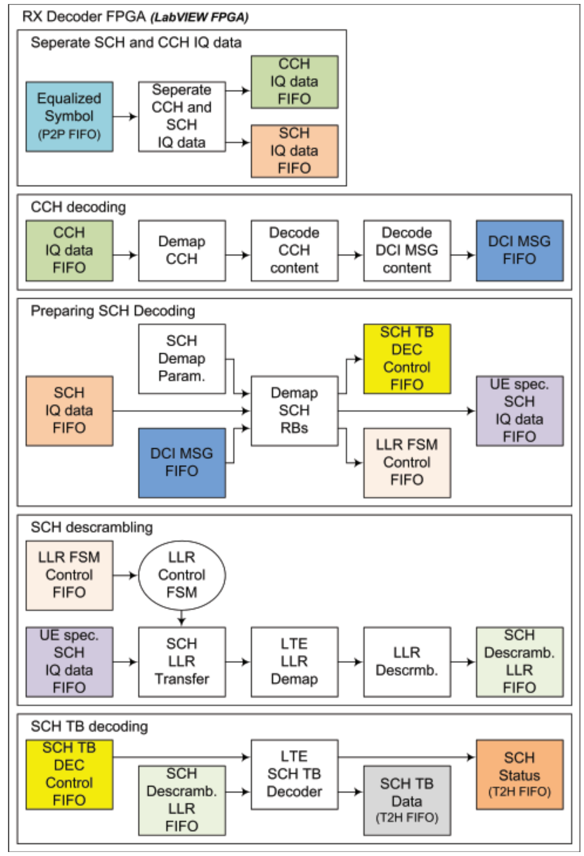


Figure 8: Detailed view of RX Decoder FPGA Architecture

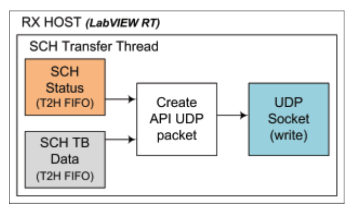


Figure 9: Detailed view of RX Host Architecture

4.2.5 *RX_DEC_FPGA_B - CCH Decoding*

The CCH IQ data is now demapped, descrambled and decoded. The content of the decoded DCI message is evaluated and passed to the DCI message FIFO.

4.2.6 *RX_DEC_FPGA_C - Preparing SCH Decoding*

With the decoded DCI information, the SCH IQ data is demapped according to the used RBs. The UE specific SCH IQ data is written to a FIFO. The SCH decoder control and LLR FSM control parameters are written to FIFOs as well.

4.2.7 *RX_DEC_FPGA_D - SCH descrambling*

Now the SCH data is demapped and decrambled usign the LLR algorithm.

4.2.8 *RX_DEC_FPGA_E - SCH TB decoding*

The descrambled SCH TB data will now be decoded with a Xilinx LTE DL Channel decoder. The status of the SCH decoding as well as the decoded SCH data is written to T2H FIFOs.

4.2.9 *RX_RT_A - SCH Transfer Thread*

The status of the SCH decoding is read every millisecond by the Host application. If SCH TB data is available it is read from the SCH TB data T2H FIFO and transfer together with the SCH status information to the higher layers using a UDP connection.

5 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 want 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.

5.1 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. Almost Blank sub frame (ABS) [19] is one of the proposed 3GPP eICIC mechanism that 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. 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. 10 shows the architecture of CROWD testbed to implement ABS algorithm.

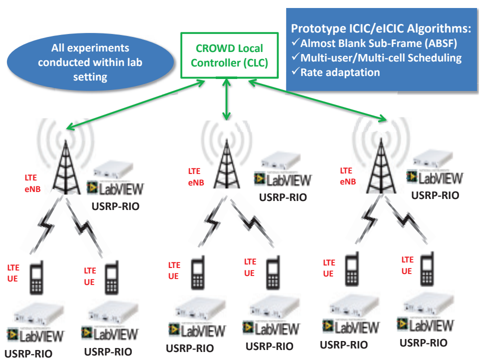


Figure 10: LTE eICIC/ICIC Prototyping

5.2 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 [20–23] 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 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 L1-L2 API to enable study of coexistence algorithms. Fig. 11 shows the architecture of LTE/WiFi Coexistence prototyping within CROWD testbed.

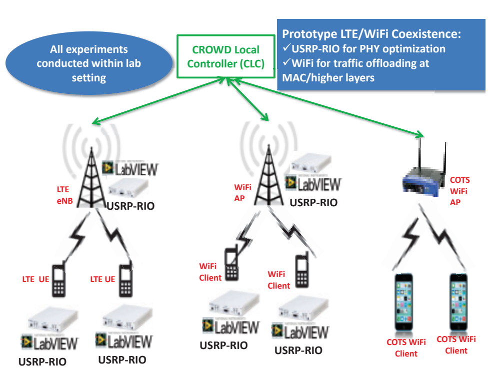


Figure 11: LTE/WiFi Coexistence Prototyping

5.3 Device-to-Device (D2D) Communication in LTE

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. 12). 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 enhancements. 3GPP is already considering to incorporate this technology in Release-12 [24] as public safety feature. Fig. 12 shows the overall system architecture for prototyping LTE D2D algorithms in CROWD testbed.

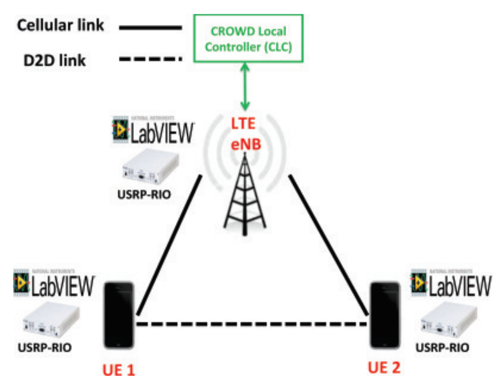


Figure 12: LTE-Direct Prototyping

5.4 Coordinated access for Machine-to-Machine (M2M)/Machine-type-Communications (MTC)

The increasing demand for connecting the billions of sensors, machines and devices to access network is a great challenge for the service providers, network operators, sensor manufacturers due to limited bandwidth, Energy efficiency, mobility and security concerns over the coordinated access. Hence, in order to address M2M/MTC challenges to use the LTE networks as coordinated access network to support large number of sensors/devices, large number of researchers are working on the PHY/MAC for M2M/MTC. CROWD platform as shown in Fig. 13, provides researchers the ability for prototyping cognitive-radio MAC for M2M/MTC communications that addresses the challenges stated above where bandwidth required per device is not large but the number of devices communicating is much larger than the currently supported configuration in LTE network. We plan to use USRP E-310 for prototyping MTC devices as it is geared towards small form-factor modules and features a ZynQ SOC, which contains ARM Processor + Xilinx FPGA. The platforms provide the framework mechanism for coordinated access in order to design and prototype the following:

- M2M/MTC and IoT testbed for experiments
- Sensor applications
- Generic Physical and MAC layer for M2M/MTC communications
- Usage of LTE protocols for M2M communications
- Energy efficient and Security protocols for M2M/MTC communications
- Emulation for M2M/MTC applications
- Backhaul/Mobility for M2M/MTC systems

5.5 Cloud Radio Access Network (C-RAN)

C-RAN [25] 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, Software-Defined Network (SDN) approaches, and advanced remote antenna/radio head techniques. C-RAN architecture replaces conventional terrestrial cell site base stations are 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) sited in different geographical locations in order to provide full coverage of an area. Co-operative

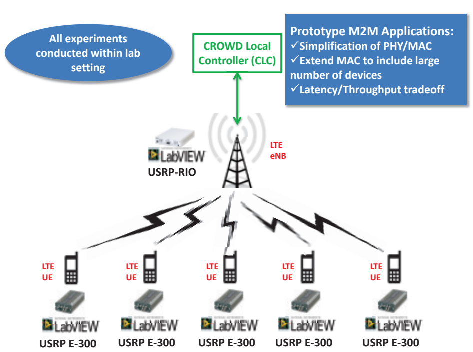


Figure 13: M2M/MTC Prototyping

radio with distributed antenna equipped by Remote Radio Head (RRH) 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 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. 14 shows the example architecture for C-RAN prototyping using CROWD testbed.

Table 1: 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)

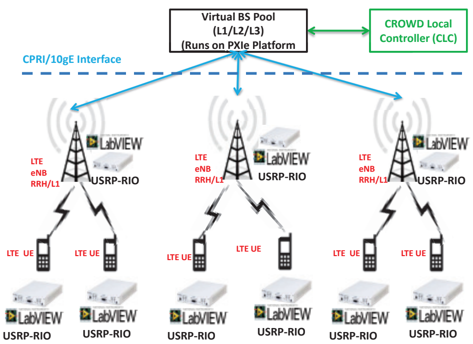


Figure 14: Cloud RAN (C-RAN) Prototyping

6 RESULTS

In this section, we describe the initial results from our testbed highlighting the physical layer performance and also highlight the feasibility of our experiments in an indoor setting. 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 1. 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.

6.1 Downlink RF Characterization

Here, we highlight the initial results of RF calibration and MCS-SNR mapping for different pre-defined BLER thresholds. This calibration was performed for the full bandwidth of 20MHz. These results are then used in the SNR-MCS mapping tables in LTE MAC Scheduler to make scheduling decisions. Fig. 15 illustrates the required SNR for achieving the pre-defined BLERs for all MCSs. Although the desired BLER before HARQ is 0.1 in LTE, we opt to show the results BLERs of 0.01 and 0.0001. Currently, we aim for BLER of 0.0001 because our current implementation does not support HARQ. As observed in the figure, the required SNR for a given BLER increases as we use higher MCSs. Because higher MCSs carry more data and have lower coding rate, they are more susceptible to errors, hence, they desired higher SNR. The high variations after MCSs 9 and 16 are due to change of Modulation schemes. Finally, lower BLERs require higher SNR in order to better harness the impact of channel impairments.

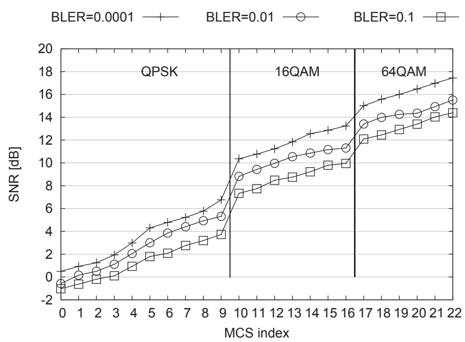


Figure 15: MCS-SNR mapping for BLERs of 0.1, 0.01, and 0.0001.

6.2 Almost Blank Subframe (ABS) PHY Calibration

ABS algorithm implies the muting of data sub carriers when there is no MAC PDU from higher layers. However, we still need to transmit DL Reference Symbols (RS), PSS, SSS, PDCCH to keep physical layer synchronization. In figures below, we illustrate the power level reduction on an average of subframe with/without ABS activation. Fig. 16 shows the signal magnitude comparison at the output of FFT for data and pilot subcarriers. We can see from the results of Fig. 16 that after enabling ABS, there is considerable reduction of signal magnitude of data sub-carriers, whereas pilot sub-carriers are not affected due to application of ABS. Fig. 17 shows the reduction in average power at the input of FFT. We see from the results of Fig. 17 that there is about 7 dB reduction in the average received signal power at the input of FFT at the receiver. Since, there ABS results in the suppression of only data carriers and not pilot carriers. This results in ideal average power reduction of 10log(6)=7.8 dB (as there is one pilot sub-carrier for every 5 data sub-carriers) in each symbol. In these calculations, we do not take into account the fact that PSS, SSS, PDCCH are still transmitted during ABS frame. Hence, the results of these two figures only correspond to symbols that carry only PDSCH channel. These preliminary results only indicate the receiver characteristics when ABS is applied, however in future we plan to conduct more extensive experiments in an indoor setting on the effect of enabling ABS in a multi-cell environment.

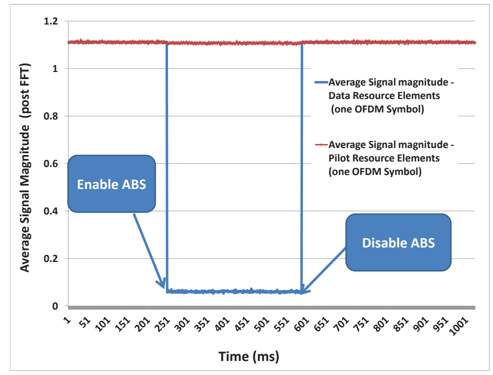


Figure 16: Post FFT Signal Magnitude Comparison (before/after applying ABS)

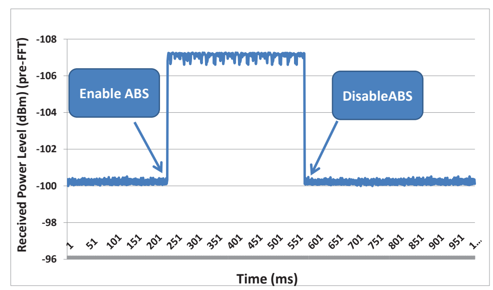


Figure 17: Average Received Signal Power (pre-FFT) (before/after applying ABS)

7 CONCLUSION

In this paper, we presented a generic LTE MAC/PHY framework that can be used to protototype complex cellular use cases within the SDN framework. We would like to emphasize the modularity of NI PXI Platform along with LabVIEW environment are the key factors that allowed us to achieve significant results in CROWD project. The integration of open source protocol stack also lends itself to much more cost-effective solution compared to other commercial LTE offerings. The proposed PHY Layer along with MAC/PHY API is the basis for integration with open source protocol stacks, like NS-3 LENA. The integration with open source system simulator, like NS-3 allows much shorter time from simulations to prototyping and our platform lends itself to solve mutiplicity of use cases such as eICIC, M2M, LTE-D, LTE/WiFi Coexistence and C-RAN. We believe that these use cases pose fundamental challenges for dense deployments and prototyping them using CROWD SDN framework can provide lot of insights into algorithms/frameworks for next generation wireless networks. We also showed some preliminary results on the PHY layer and we plan to provide more results in future for each of the proposed individual use cases.

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