Real-Time Prototyping of 5G Software-Defined Networks: Part 3

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Abstract

This is the final white paper of the three-part series on the NI LTE MAC/PHY prototyping system. This installment provides a system-level overview of the LTE MAC/PHY prototyping system with descriptions of the hardware and software architectures. It also presents functional descriptions of the application software, which provides insight on how to use the system for the prototyping of wireless network-related research. To learn more about the LTE MAC/PHY prototyping system, see parts 1 and 2 of the series:

- Real-Time Prototyping of 5G Software-Define Networks: Part 1
- Real-Time Prototyping of 5G Software-Define Networks: Part 2

Introduction

Computer-based simulations, although useful in generating nominal performance benchmarks of wireless communication systems, often make inaccurate assumptions of various system model components that largely limit the ability to predict how an actual system will behave in practice. Therefore, functional prototypes that operate over real-world wireless channel conditions in real time are essential to determine the feasibility of new technologies and the extent to which their promised gains in performance can be achieved. Such mandatory prototypes and field trials are necessary to gain broader acceptance of next-generation technologies within the wireless industry.

Although necessary, prototyping has traditionally presented challenges that stem from the many complexities associated with the various layers in the network communication stack including the PHY, MAC, and network layers. Furthermore, each layer traditionally has required the use of highly disparate development tools and the expertise of skilled researchers and engineers to perform tasks such as programming FPGAs and designing RF circuits. Consequently, such prototyping design cycles are oftentimes lengthy and costly.

To address the challenges of prototyping real-time wireless communication systems, NI offers a number of software defined radio (SDR) prototyping systems with capabilities that satisfy a variety of hardware and software requirements for the following use cases and specifications:

- Prototyping of base stations and terminals
- Support of RF frequencies both above and below 6 GHz
- Support of bandwidths ranging from 40 MHz to 2 GHz
- Scalable CPU and FPGA architectures for additional processing resources
- Customizable PHY layer reference designs for LTE, 802.11, and other 5G technologies
Unified and comprehensive software design tools supporting both CPUs and FPGAs

With such tools and capabilities, the NI SDR prototyping system can be used for conducting real-time, over-the-air experiments of heterogeneous networks. As an example, this paper describes a prototyping system that combines the NS-3 open-source upper-layer protocol stack with the NI LTE PHY layer. In general, this approach of interfacing open-source tools with the NI SDR prototyping system can be extended to access technologies other than LTE such as 802.11 and other 5G eMBB technologies. Furthermore, as the source code for the entire stack from the PHY layer to the network layer is available and modifiable, the prototyping system can also be used in the following research areas:

- Latency reduction optimizations of the full system stack (shortened TTI)
- Interference coordination and cancellation algorithms (CoMP, eICIC, and so on)
- Flexible numerologies and protocols for new waveforms
- Narrowband Internet of Things protocols
- New SDN and network slicing
- CRAN and functional splits

To aid researchers in this journey toward 5G, NI offers flexible SDR prototyping solutions that help scientists and engineers make rapid progress with the development of new algorithms. The NI LabVIEW Communications LTE Application Framework has proven a useful starting point in the exploration of 4G enhancements [1] and proposed 5G PHY techniques [2]. This document presents the NI MAC/PHY prototyping system as an example that illustrates how a third-party upper-layer protocol stack or MAC can be incorporated with the LTE physical-layer implementation to facilitate real-time, over-the-air transmission.

For a video demonstration and overview of the LTE MAC/PHY prototyping system, click on the image below.

![Image](image.jpg)

**Figure 1. Overview and Demonstration of the LTE MAC/PHY Prototyping System**

**MAC/PHY Prototyping System**

Figures 2a and 2b show a system-level diagram of the MAC/PHY prototyping system. Figure 2a shows a high-level diagram depicting the functional components of the LTE eNB and UE consisting of the NS-3 upper-layer stack and the **LTE application framework** real-time PHY layer, which are joined together with high-speed UDP interfaces. Figure 2b depicts the hardware architecture of the prototyping system and a mapping of the various PHY layer and upper-layer software components to the individual hardware
devices. The following is a description of the various hardware devices within the system and their respective software components.

**Host Controller**

The NI PXIe-8880 controller is equipped with a 2.3 GHz Intel eight-core Xeon processor and up to 24 GB of RAM. The controller is also equipped with a high-speed 24 GB/s PXI Express bus interface for high-throughput data transfers with other devices on the PXI Express backplane such as NI FlexRIO FPGA modules. The CPU runs the NI Linux Real-Time OS that provides greater determinism compared to non-real-time OSs for time-critical operations such as those associated with NS-3 and the host interface of the LTE application framework. This ensures that NS-3 executes in real time and can complete operations on a 1 ms subframe basis as dictated by the LTE standard.

**Software Defined Radios**

The NI USRP RIO is a complete SDR solution equipped with a Xilinx Kintex-7 FPGA, dual high-speed analog-to-digital converters/digital-to-analog converters, and two RF transceivers. The USRP RIO comes in a number of different models that support various carrier frequencies and bandwidth options that can be used for different applications. For the MAC/PHY prototyping system, the LTE PHY layer signal processing is implemented on an FPGA to ensure real-time execution of the system. Moreover, control of the RF transceiver hardware is also implemented on the FPGA.

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**Figure 2. MAC/PHY Prototyping System Overview**
System Hardware Configuration

The following hardware components are required for the LTE MAC/PHY prototyping system:

- **NI PXIe-1082** chassis
- **PXIe-8880** or **NI PXIe-8135** controller
- **USRP RIO** (for example, NI USRP-2954R) with the **NI PXIe-MXI Express Interface Kit**

Figure 3 shows the primary hardware setup. Note that all hardware configurations require a Microsoft Windows PC to control the system. The NS-3 MAC executes on the same PXI Controller that runs the NI Linux Real-Time OS to guarantee real-time performance. The LTE PHY executes on an FPGA target on a cabled USRP RIO device.

![Figure 3. Recommended Deployment Option](image)

System Software Architecture

The following software is required to use the LTE MAC/PHY prototyping system:

- **LabVIEW Communications System Design Suite 2.0** with the **NI Linux Real-Time OS**
- **LTE application framework 2.0.1**
- **Open-source network simulator NS-3**

Figure 4 shows a system diagram that depicts each of the hardware targets for a single eNB and single UE configuration and the corresponding software components executing on them. The two PXI systems shown to the far left and far right of the diagram represent the eNB and UE, respectively. Within each of the devices are block diagrams representing the various hardware elements within the NI PXI Chassis, such as the controller and FPGA module, and the various software components executing within each target. The NI Linux Real-Time PXI controllers run NS-3, the host interface of the LTE PHY, and the L1-L2 API linking the two together, and the FPGA module runs the real-time LTE PHY.
At the center of Figure 4 is a Windows machine used to control both the eNB and UE. The Windows machine is connected to each target through Ethernet and performs tasks such as deploying and running project executables on each PXI target, configuring the overall network of devices, and monitoring the behavior of each PXI system through plots and terminal outputs.

The system can be scaled to support additional eNBs and UEs to form larger LTE wireless networks where each device possesses similar hardware and software architectures like that shown above. And as the source code for every device is open and modifiable, each device can be customized with unique upper-layer stack protocols to support capabilities such as the rapid handoff of UEs across neighboring cells or novel interference cancellation algorithms. The flexibility and hardware capabilities of the LTE MAC/PHY prototyping system enable it to be used to conduct real-time over-the-air trials for the evaluation of 5G wireless networks.

Figures 5 and 6 show the PHY and L1-L2 user interfaces of the MAC/PHY prototyping system for the eNB. Note that the highlighted MCS parameter and RB allocation can be configured by the NS-3 MAC during run time. Further, the execution of the NS-3 binary can be started and stopped from within the LabVIEW GUI and its output is also piped out to the GUI for additional convenience.
The NS-3 LTE module includes a C++ implementation of LTE layers 1-3 (RRC, PDCP, RLC, MAC, and PHY emulation) for the eNB and UE and supports the use of multiple eNBs and UEs connected to the core network (MME, SGW, and PGW). Furthermore, NS-3 supports X2 links between multiple eNBs that enable hand-over procedures and interference coordination techniques. Other network functionalities supported by NS-3 that are essential in the simulation of 5G wireless networks include the following [3]:
• Radio resource management
• QoS-aware packet scheduling
• Intercell interference coordination
• Dynamic spectrum access

NS-3 also includes an implementation of the FemtoForum MAC Scheduler API, which simulates scheduling decisions on the use of radio resources for UEs requesting access to the core network. Moreover, the FemtoForum MAC Scheduler API supports an interface to external applications and includes a basic HARQ model with corresponding error models.

NS-3 is designed as an event-driven system that operates based on queues with scheduled events that are executed at discrete time points. Although not intended to be used in a real-time manner for high-rate streaming applications, the LTE MACPHY prototyping system can schedule NS-3 operations in real time with use of the NI Linux Real-Time OS. This is critical for error-free, real-time stack operations, which occur on a 1 ms subframe time boundary. As such, NS-3 operates under this time constraint and does so successfully for the given implementation of the prototyping system.

Ordering and Purchasing Information

The project files for the LTE MACPHY prototyping system, including all the source code related to both NS-3 and the L1-L2 interface, are available for free with the purchase of the required NI hardware and software products: NI SDR hardware, LabVIEW Communications 2.0, and the LTE application framework 2.0.1. Note that NS-3 is not sold by NI, but is free for download at the NS-3 homepage.

For more information on the LTE MACPHY prototyping system and to request a quote for the system shown below in Figure 3 and listed in Table 1, please contact your local NI sales representative or email labview.communications@ni.com.

<table>
<thead>
<tr>
<th>Description</th>
<th>Qty</th>
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<tbody>
<tr>
<td>PXle-1082 chassis</td>
<td>2</td>
</tr>
<tr>
<td>PXle-8880 controller</td>
<td>2</td>
</tr>
<tr>
<td>USRP-2954R with PXle-MXI Express Interface Kit</td>
<td>2</td>
</tr>
<tr>
<td>LabVIEW Communications System Design Suite 2.0 with NI Linux Real-Time</td>
<td>1</td>
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<tr>
<td>LTE application framework 2.0.1</td>
<td>1</td>
</tr>
<tr>
<td>Open-source network simulator NS-3 (Not sold by NI)</td>
<td>1</td>
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Table 1. List of Hardware and Software for the System Configuration Shown in Figure 6
Additional Resources

To learn more about NI solutions for LTE MAC/PHY prototyping, visit the following websites:

- LabVIEW Communications Application Frameworks—Learn more about other application frameworks for LTE and 802.11.
- LabVIEW Communications—Learn more about LabVIEW Communications for prototyping wireless communication systems.
- USRP RIO—Learn more about the USRP RIO software defined radio.
- 5G Research—Learn more about NI and other 5G research activities.

References


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