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OAI Reference Architecture for 5G and 6G Research with USRP

From Ettus Knowledge Base

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Application Note Number

AN-956

Abstract

This Application Note presents a reference design for using the Eurecom OpenAirInterface (OAI) software stack to implement 5G NR Stand-Alone (SA) systems on the USRP N300, N310, N320, N321, X410 radio devices. The reference design covers the base station (gNB), the user equipment (UE), and the Core Network (CN) components of the network. Three types of UE are used: a UE running on a USRP radio; a wireless modem module UE; and a commercial (COTS) handset/phone. The reference design supports operation in Frequency Range 1 (FR1), and support for operation in FR2 will be added at a future date. The various aspects of installing, configuring, and running the hardware and software components of the network are discussed in detail, along with a discussion of expected results, methods to benchmark and monitor the system, and troubleshooting steps.

The solution brochure for the OAI Reference Architecture for 5G and 6G Research with the USRP can be downloaded [here](#).

An overview of using OAI Software for 5G and 6G research at this webpage [here](#).

You can learn more about other solutions for 5G and 6G Wireless Research and Prototyping at the webpage [here](#).

NI Part Numbers

The table listed below shows the contents of several pre-configured bundles that can serve as a useful starting point for the OAI USRP Reference Architecture, which can be ordered using the corresponding NI part number. For more information about these bundles, please contact us at sales@ni.com.

Pre-Configured Bundles for the OAI USRP Reference Architecture

P/N	System Name	Description
868063-01	USRP X410 OAI Bundle For 5G and 6G Research Base	<ul style="list-style-type: none"> ■ OAI Welcome Card ■ USRP X410 (4 TX and 4 RX, 400 MHz BW, 1 MHz to 7.2 GHz SDR, GPSDO)
868063-02	USRP X410 OAI Bundle For 5G and 6G Research Standard	<ul style="list-style-type: none"> ■ OAI Welcome Card ■ USRP X410 (4 TX and 4 RX, 400 MHz BW, 1 MHz to 7.2 GHz SDR, GPSDO) ■ Dual 100 Gbps Ethernet PCIe Interface Kit for Ettus USRP X4xx ■ QSFP28-to-4xSFP28 Breakout Cable, 1 m ■ VERT2450 Vertical Antenna (2.4 to 2.5 and 4.9 to 5.9 GHz) Dual-Band ■ SMA Male to SMA Male Cable, 50 Ohm, 1 m
868063-03	USRP N310 OAI Bundle For 5G and 6G Research Base	<ul style="list-style-type: none"> ■ OAI Welcome Card ■ USRP N310 (ZYNQ-7100, 4 Channel, 10 MHz to 6 GHz, 10 Gbps Ethernet)
868063-04	USRP N310 OAI Bundle For 5G and 6G Research Standard	<ul style="list-style-type: none"> ■ OAI Welcome Card ■ USRP N310 (ZYNQ-7100, 4 Channel, 10 MHz to 6 GHz, 10 Gbps Ethernet) ■ Dual 100 Gbps Ethernet PCIe Interface Kit for Ettus USRP X4xx ■ 10 Gbps SFP+ Ethernet Cable, 3 m ■ VERT2450 Vertical Antenna (2.4 to 2.5 and 4.9 to 5.9 GHz) Dual-Band ■ SMA Male to SMA Male Cable, 50 Ohm, 1 m
868063-05	USRP N321 OAI Bundle For 5G and 6G Research Base	<ul style="list-style-type: none"> ■ OAI Welcome Card ■ USRP N321 (Non-TPM, 2 TX/RX Channels, 200 MHz BW, with LO Distribution)
868063-06	USRP N320 OAI Bundle For 5G and 6G Research Base	<ul style="list-style-type: none"> ■ OAI Welcome Card ■ USRP N320 (Non-TPM, 2 TX/RX Channels, 200 MHz BW)

Overview of the USRP N300 and N310

The USRP N300 and N310 are a networked software defined radio that provides reliability and fault-tolerance for deployment in large scale and distributed wireless systems. This device simplifies control and management of a network of radios by introducing the unique capability to remotely perform tasks such as debugging, updating software, rebooting, factory resetting, self-testing, and monitoring system health. The USRP N310 is an all-in-one device that

includes two AD9371 transceivers, the Zynq-7100 SoC baseband processor, two SFP+ ports, a built-in GPSDO module, and various other peripheral and synchronization features.

The N300 features:

- Xilinx Zynq-7035 FPGA SoC
- Dual-core ARM A9 800 MHz CPU
- 2 RX, 2TX in half-wide RU form factor
- 10 MHz – 6 GHz extended frequency range
- Up to 100 MHz of instantaneous bandwidth per channel
- RX, TX filter bank
- 16 bit ADC, 14 bit DAC
- Configurable sample rates: 122.88, 125, and 153.6 MS/s
- Two SFP+ ports (1 GbE, 10 GbE, Aurora)
- RJ45 (1 GbE)
- 10 MHz clock reference
- PPS time reference
- Built-in GPSDO
- 1 Type A USB host port
- 1 micro-USB port (serial console, JTAG)
- Watchdog timer
- OpenEmbedded Linux
- High channel density
- Reliable and fault-tolerant deployment
- Remote management capability
- Stand-alone operation
- USRP N300 **does not** contain a Trusted Platform Module



The N310 features:

- Xilinx Zynq-7100 FPGA SoC
- Dual-core ARM A9 800 MHz CPU
- 4 RX, 4TX in half-wide RU form factor
- 10 MHz – 6 GHz extended frequency range
- Up to 100 MHz of instantaneous bandwidth per channel
- RX, TX filter bank
- 16 bit ADC, 14 bit DAC
- Configurable sample rates: 122.88, 125, and 153.6 MS/s
- Two SFP+ ports (1 GbE, 10 GbE, Aurora)
- RJ45 (1 GbE)
- 10 MHz clock reference
- PPS time reference
- External RX, TX LO input ports
- Built-in GPSDO
- 1 Type A USB host port
- 1 micro-USB port (serial console, JTAG)
- Trusted Platform Module (TPM) v1.2
- Watchdog timer
- OpenEmbedded Linux
- High channel density
- Reliable and fault-tolerant deployment
- Remote management capability
- Stand-alone operation



For more detailed technical information about the USRP N300 and N310, please reference the N300/N310 Hardware Resource Page.

For more information about getting started with the USRP N300 and N310, please reference the Getting Started Guide.

Overview of the USRP N320 and N321

The USRP N320 and N321 are a networked software defined radio that provides reliability and fault-tolerance for deployment in large scale and distributed wireless systems. This is a high performance SDR that uses a unique RF design by Ettus Research to provide 2 RX and 2 TX channels in a half-wide RU form factor. Each channel provides up to 200 MHz of instantaneous bandwidth, and covers a frequency range from 3 MHz to 6 GHz. The baseband processor uses the Xilinx Zynq-7100 SoC to deliver a large user programmable FPGA for real-time, low latency processing and a dual-core ARM CPU for stand-alone operation. Support for 1 GbE, 10 GbE, and Aurora interfaces over two SFP+ ports and 1 QSFP+ port enables high throughput IQ streaming to a host PC or FPGA coprocessor. A flexible synchronization architecture with support for LO sharing for TX and RX, 10 MHz clock reference, PPS time reference, GPSDO,

and White Rabbit enables implementation of phase coherent MIMO testbeds. The USRP N320 leverages recent software developments in UHD to simplify control and management of multiple devices over the network with the unique capability to remotely administrate tasks such as debugging, updating software, rebooting, resetting to factory state, and monitoring system health.

The USRP N320 features:

- Xilinx Zynq-7100 FPGA SoC
- Dual-core ARM A9 800 MHz CPU
- 2 RX, 2 TX in half-wide RU form factor
- 3 MHz - 6 GHz frequency range
- Up to 200 MHz of instantaneous bandwidth per channel
- Sub-octave RX, TX filter bank
- 14 bit ADC, 16 bit DAC
- Configurable sample rates: 200, 245.76, 250 MS/s
- Two SFP+ ports (1 GbE, 10 GbE, Aurora, White Rabbit)
- One QSFP+ port (2x 10Gb / Aurora)
- RJ45 (1 GbE)
- 10 MHz clock reference
- PPS time reference
- External RX, TX LO input ports
- Built-in GPSDO
- 1 Type A USB host port
- 1 micro-USB port (serial console, JTAG)
- Trusted Platform Module (TPM) v1.2
- Watchdog timer
- OpenEmbedded Linux
- Reliable and fault-tolerant deployment
- Remote management capability
- Stand-alone operation



The USRP N321 features:

- Xilinx Zynq-7100 FPGA SoC
- Dual-core ARM A9 800 MHz CPU
- 2 RX, 2 TX in half-wide RU form factor
- 3 MHz – 6 GHz frequency range
- Up to 200 MHz of instantaneous bandwidth per channel
- Sub-octave RX, TX filter bank
- 14 bit ADC, 16 bit DAC
- Configurable sample rates: 200, 245.76, 250 MS/s
- Two SFP+ ports (1 GbE, 10 GbE, Aurora, White Rabbit)
- One QSFP+ port (2x 10Gb / Aurora)
- RJ45 (1 GbE)
- 10 MHz clock reference
- PPS time reference
- External RX, TX LO input ports
- LO Distribution for up to 128x128 MIMO
- Built-in GPSDO
- 1 Type A USB host port
- 1 micro-USB port (serial console, JTAG)
- Trusted Platform Module (TPM) v1.2
- Watchdog timer
- OpenEmbedded Linux
- Reliable and fault-tolerant deployment
- Remote management capability
- Stand-alone operation



For more detailed technical information about the USRP N320 and N321, please reference the N320/N321 Hardware Resource Page.

For more information about getting started with the USRP N320 and N321, please reference the Getting Started Guide.

Overview of the USRP X410

The USRP X410 is a high-performance, multi-channel software defined radio. The SDR is designed for frequencies from 1 MHz to 7.2 GHz, tunable up to 8 GHz and features a two-stage superheterodyne architecture with 4 independent TX and RX channels capable of 400 MHz of instantaneous bandwidth each. Digital interfaces for data offload and control include two QSFP28 interfaces capable of 100 GbE[1], a PCIe Gen3 x8 [3] interface, as well standard command, control, and debug interfaces: USB-C JTAG, USB-C console, Ethernet 10/100/1000. The USRP X410 is an all-in-one device built on the Xilinx Zynq Ultrascale+ ZU28DR RF System on Chip (RFSoc) with built-in digital up and down conversion and onboard Soft-Decision Forward Error Correction (SD-FEC) IP.

The USRP X410 features:

- High channel density
- Reliable and fault-tolerant deployment
- Stand-alone (embedded) or host-based (network streaming) operation
- Fully integrated and assembled (the USRP X410 does not support swappable daughtercards)
- 1 MHz to 7.2 GHz frequency range (tunable up to 8GHz)
- Up to 400 MHz of instantaneous bandwidth per channel
- 4 RX, 4 TX in half-wide RU form factor
- Xilinx Zynq-Ultrascale+ ZU28DR RFSoc
- 12 bit ADC, 14 bit DAC
- IQ Sample Clock rates up to 500 MS/s
- Onboard SD-FEC, DDC, DUC
- Quad-core ARM Cortex-A53 up to 1.2 GHz CPU
- Dual-core ARM Cortex-A5 MPCore up to 500 MHz
- Two QSFP28 ports (10 Gigabit Ethernet, 100 Gigabit Ethernet, Aurora)
- Two iPass+™ zHD® Interfaces (PCIe Gen3 x 8)
- RJ45 (1 GbE) [1]
- 10 MHz Clock reference
- PPS time reference
- Trig In/Out Interface
- Built-in GPSDO
- Two FPGA Programmable GPIO Interfaces (HDMI)
- 1 Type C USB host port
- 1 Type C USB port (serial console, JTAG)
- Watchdog timer
- OpenEmbedded Linux
- USRP Hardware Driver™ (UHD) open-source software API version 4.1.0 or later
- RF Network on Chip (RFNoC™) FPGA development framework
- Xilinx Vivado® 2019.1 Design Suite (license not included)
- GNU Radio support maintained by Ettus Research™ through GR-UHD, an interface to UHD distributed by GNU Radio
- [1] The RJ45 port is used for remote management of the device and does not support IQ streaming.



For more detailed technical information about the USRP X410, please reference the X410 Hardware Resource Page.

For more information about getting started with the USRP X410, please reference the X410 Getting Started Guide.

Overview of the OpenAirInterface (OAI) Software Stack

The OpenAirInterface (OAI) software provides an open-source, standards-compliant implementation of a 3GPP 5G NR stack that runs on a commodity x86 CPU and a USRP radio device. OAI was initially developed by Eurecom, which is a university in France. It is now managed and developed by the OpenAirInterface Software Alliance (OSA), which is a French non-profit organization that provides open-source software and tools for 4G and 5G wireless research. Further information can be found on the Eurecom website.

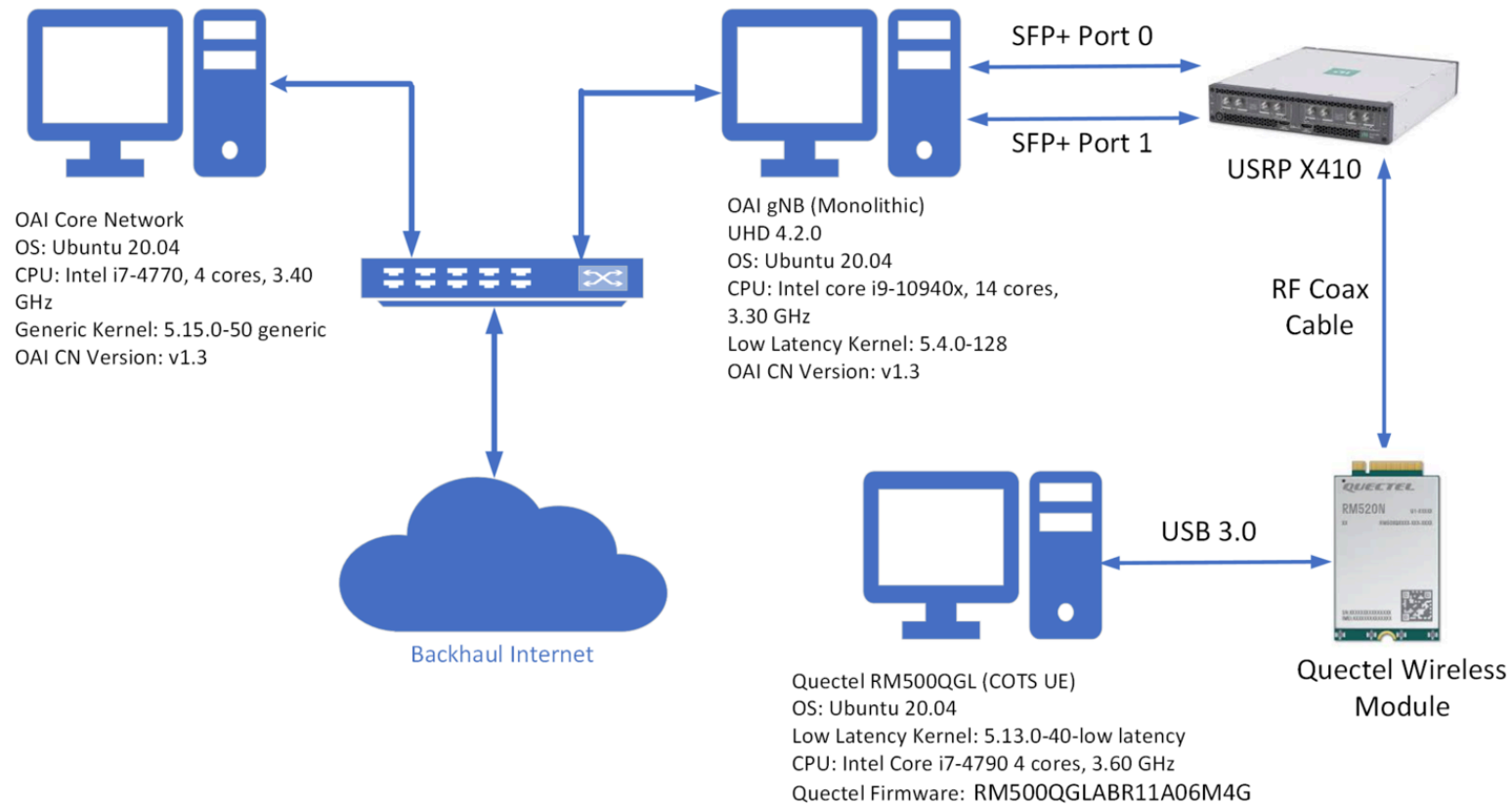
The OAI software provides a 5G NR implementation that runs in real-time and is capable of operating with commercial 5G NR handsets (UEs). The OAI software includes implementations of the gNB, the UE, and the Core Network (CN). Further information can be found on the OAI website and their GitLab repository, listed below.

- OpenAirInterface 5G Radio Access Network Project
- OAI GitLab Repository
- OAI 5G Core Network
- OAI-CN GitLab repository

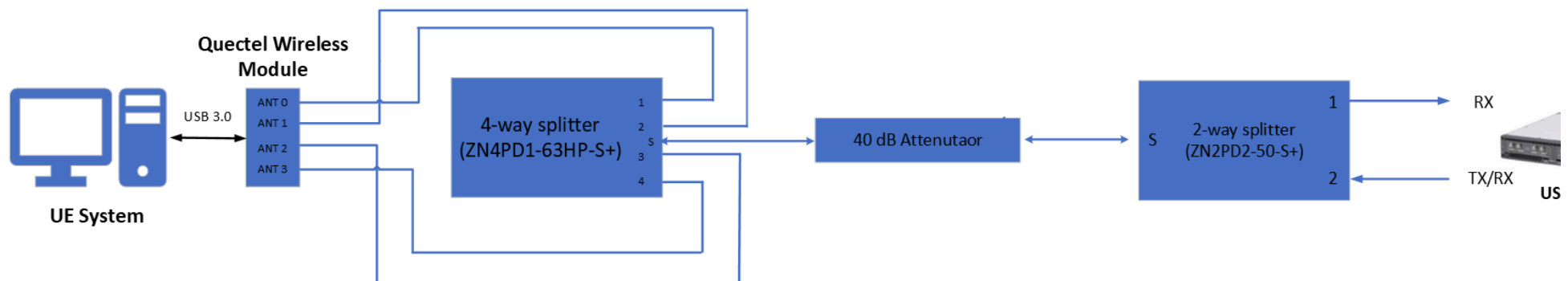
The availability of OAI source code is free for non-commercial and academic research purposes. More information about licensing can be found on the OAI website at [here](#) and [here](#).

Overview of the Reference Architecture

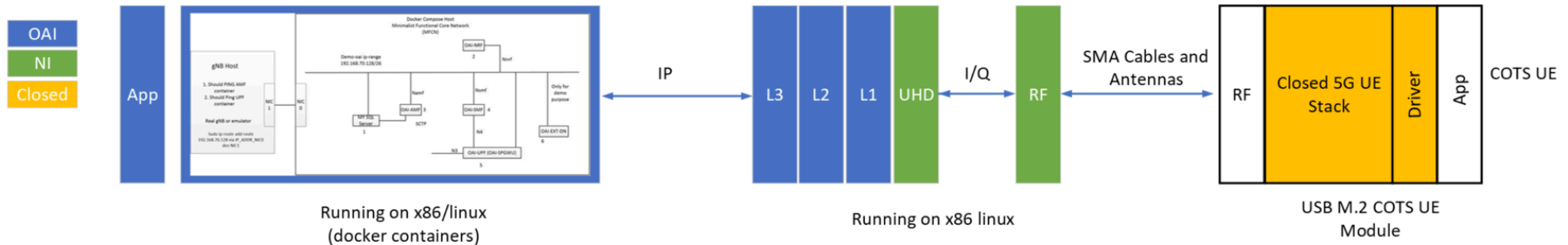
The diagram below shows the layout and architecture of this 5G OAI USRP reference architecture.



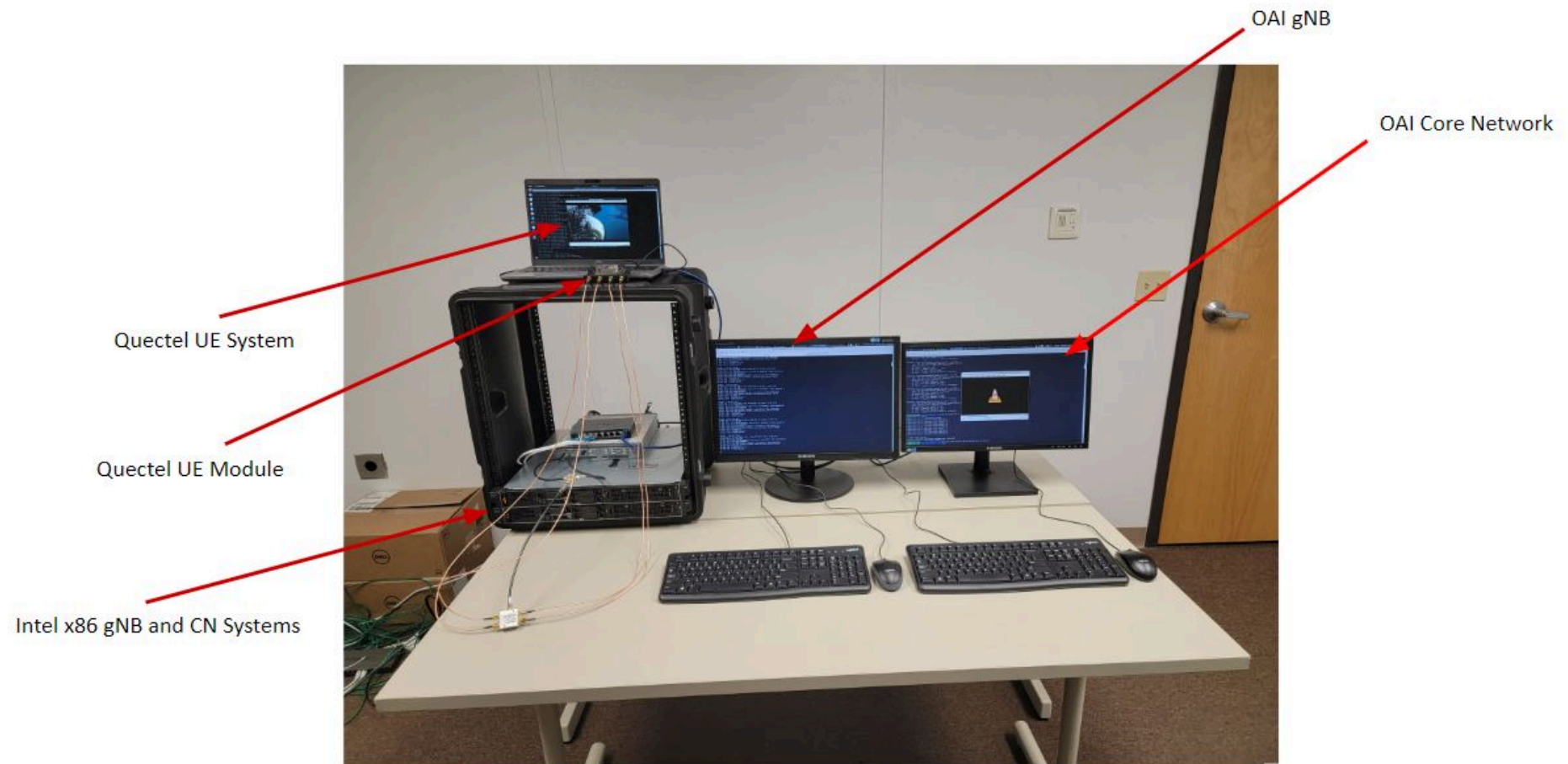
The diagram below shows the RF cable connections between the USRP X410 and the Quetel wireless modem module.

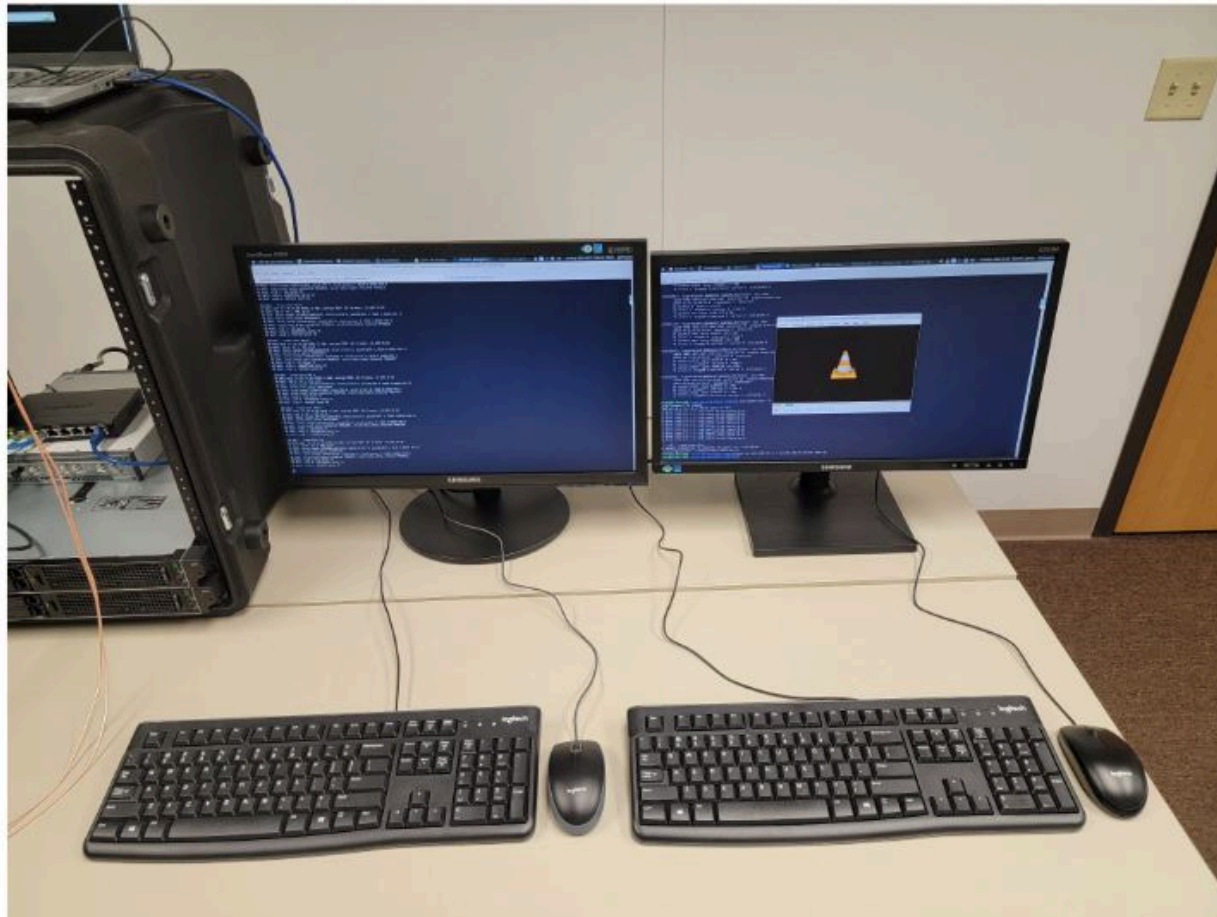


The diagram below shows the software layout and architecture across the Core Network, gNodeB, and UE systems.



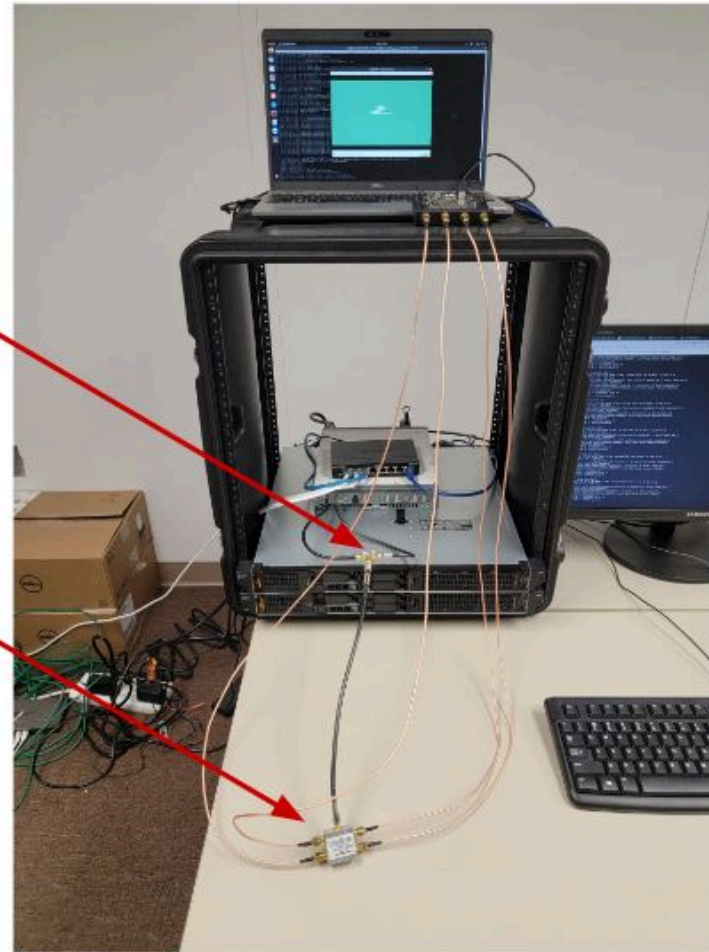
The photos below show one physical implementation of the reference architecture in the office of the authors. Note that this is not the sole valid system implementation, but it is one of many possible valid system implementations.

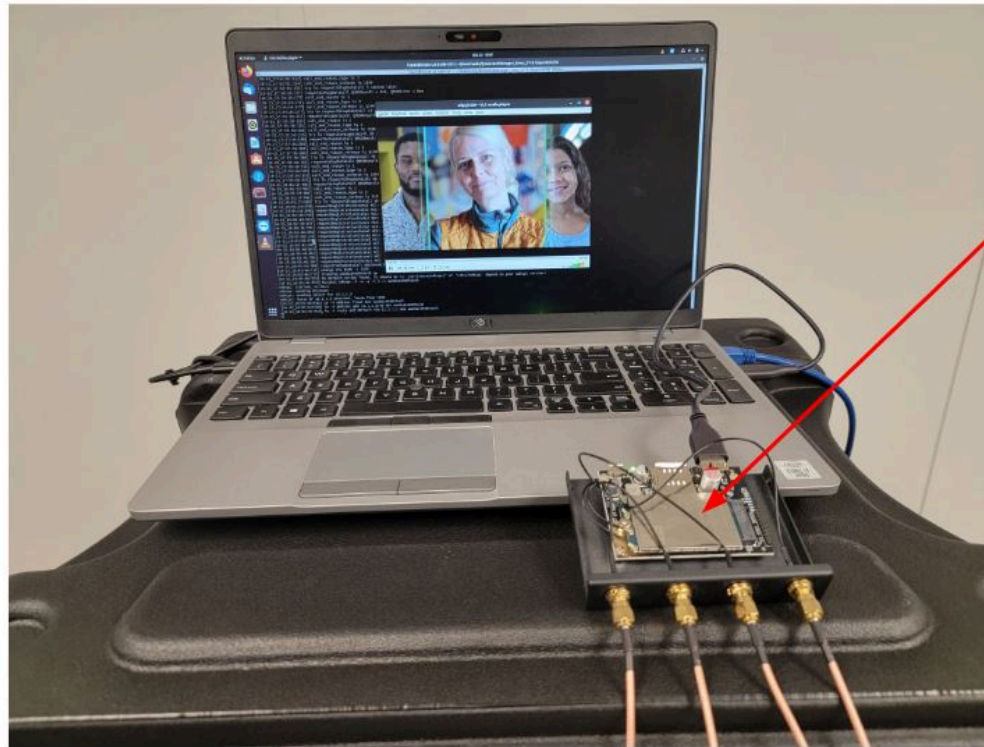




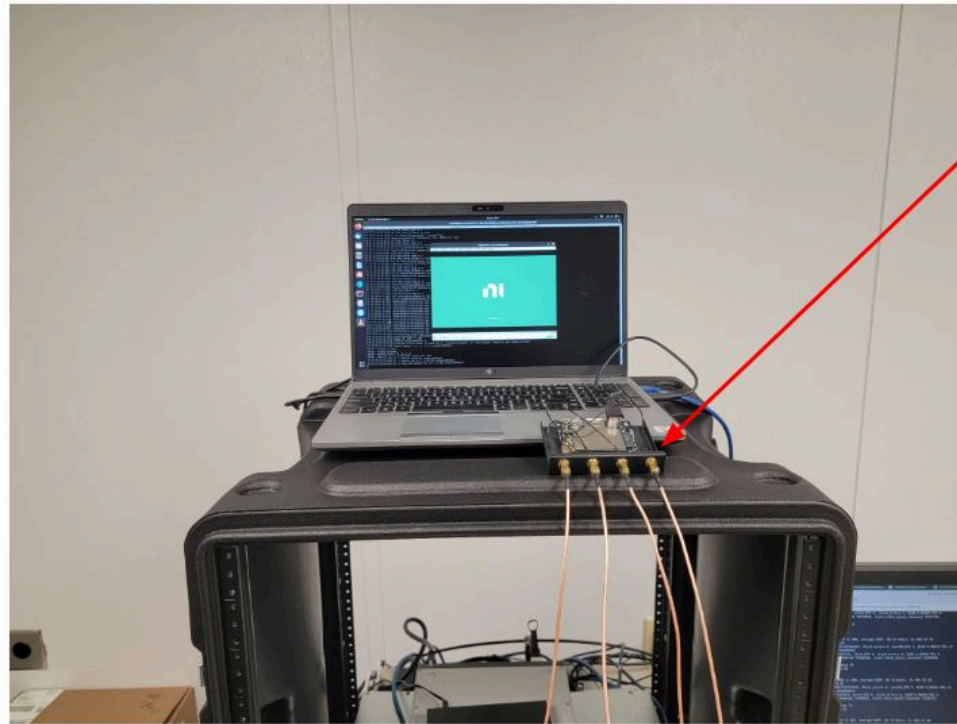
2-way RF Splitter

4-way RF Splitter



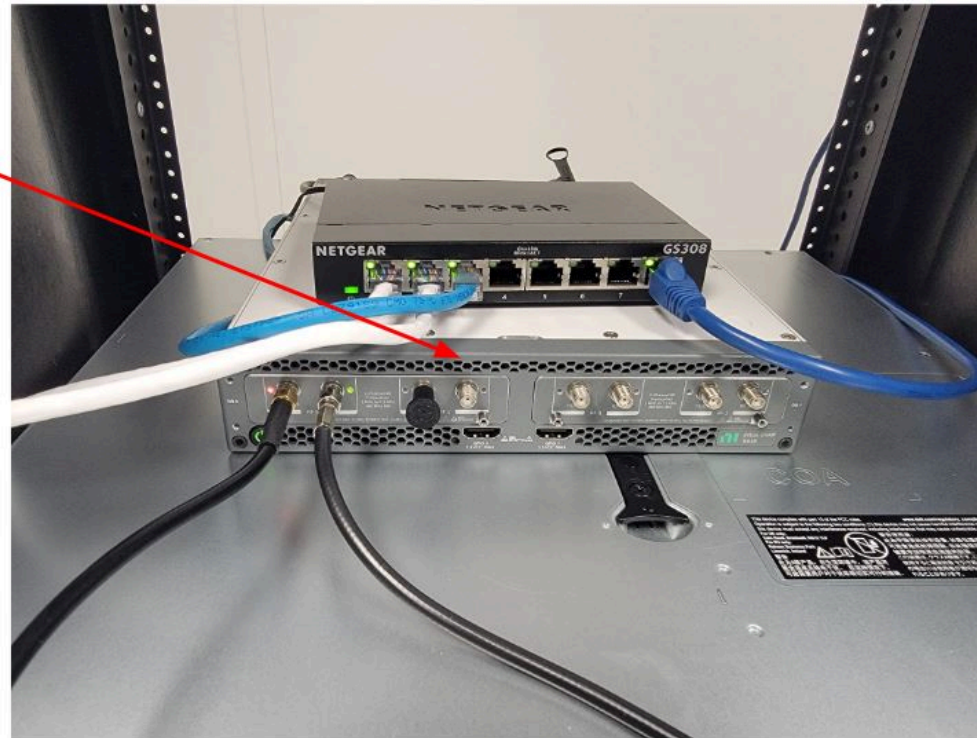


Quectel Module UE



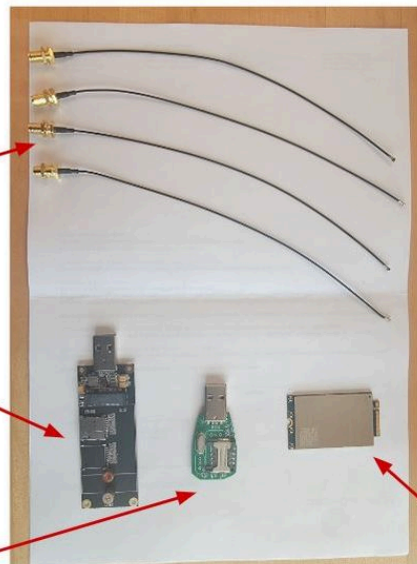
Quectel Module UE

USRP X410



Pigtail MHF4-to-SMA RF Cables

USB 3.0 / M.2 Carrier Board

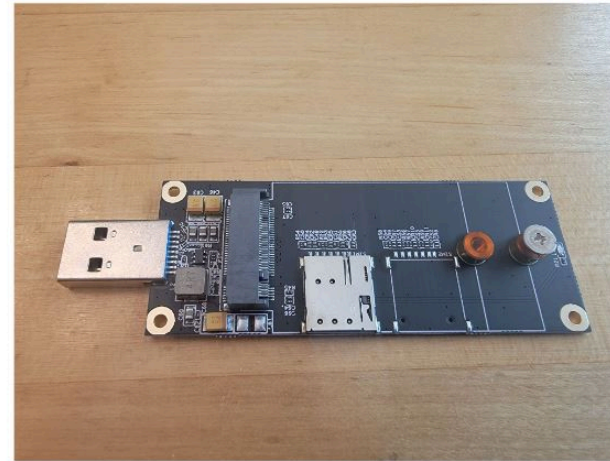
SIM Card
Reader/Writer

Quectel Module





Quectel Module



USB 3.0 / M.2 Carrier Board

Bill of Materials (BoM)

The full Bill of Materials (BoM) for the reference design is listed below. The BoM includes all the hardware components for the multiple system configuration scenarios, where the USRP N300, N310, N320, N321, X410 can be used for the gNB and the UE system, and the UE itself can be implemented with a USRP device, or with a wireless modem module, or with a COTS handset.

- Three desktop computers, with Intel Core i9 CPU, of 10th, 11th, or 12th Generation, with clock speed of minimum 4.0 GHz, with minimum 10 physical cores, and also with only NVMe disk drives. See further details about this item in the Hardware Requirements section.
- Two 10 Gbps Ethernet networks cards. We recommend the Intel X710-DA2 and the Nvidia/Mellanox MCX4121A-ACAT ConnectX-4 network cards. See further details about this item in the Hardware Requirements section.
- Two USRP devices. The USRP may be any of USRP N300, N310, N320, N321, X410. There will be one USRP for the gNB, and one USRP for the UE. The USRP devices can be mixed (i.e., the gNB could run with a USRP X410, while the UE runs with a USRP N310).
 - <https://kb.ettus.com/N300/N310>
 - <https://kb.ettus.com/N320/N321>
 - <https://kb.ettus.com/X410>
 - <https://www.ettus.com/all-products/usrp-n300/>
 - <https://www.ettus.com/all-products/usrp-n310/>
 - <https://www.ettus.com/all-products/usrp-n320/>
 - <https://www.ettus.com/all-products/usrp-n321/>
 - <https://www.ettus.com/all-products/usrp-x410/>

- One QSFP28-to-SFP28 breakout cable (NVIDIA MCP7F00-A003R26N DAC Splitter Cable Ethernet 100GbE to 4x25GbE 3m). This is only needed when using the USRP X410.
 - <https://store.mellanox.com/products/nvidia-mcp7f00-a003r26n-passive-copper-splitter-cable-ethernet-100gbe-to-4x25gbe-qsfp28-to-4xsfp28-3m-colored-26awg-ca-n.html>
 - <https://store.mellanox.com/products/nvidia-mcp7f00-a003r30l-passive-copper-splitter-cable-ethernet-100gbe-to-4x25gbe-qsfp28-to-4xsfp28-3m-colored-30awg-ca-l.html>
- One OctoClock-G. This is needed to synchronize the gNB USRP and the UE USRP. Ensure that device used is the "-G" model, which contains an internal GPSDO module. This is only needed when the UE is implemented on a USRP device.
 - https://kb.ettus.com/OctoClock_CDA-2990
 - <https://www.ettus.com/all-products/octoclock-g/>
- Four 10 Gbps Ethernet cables with SFP+ terminations. These cables are available in 0.5, 1.0, and 3.0 meter lengths. These cables are needed when using the USRP N300, N310, N320, N321, but not when using the USRP X410.
 - <https://www.ettus.com/all-products/10gige-dc/>
 - <https://www.ettus.com/all-products/10gige-1m/>
 - <https://www.ettus.com/all-products/10gige-3m/>
- Four VERT900 antennas and/or four VERT2450 antennas. You can use either of these antennas based on the bands in use. There are also many third-party vendors selling a wide variety of antennas, such as omnidirectional antennas. As long as the antenna has an 50-ohm impedance and has SMA connectors, then it can be used with the USRP radio.
 - <https://www.ettus.com/all-products/vert900/>
 - <https://www.ettus.com/all-products/vert2450/>
- One Quectel RM500Q-GL 5G wireless modem module. See further details about this item in the Hardware Requirements section.
 - <https://www.quectel.com/product/5g-rm500q-gl>
 - <https://www.quectel.com/product/5g-rm50qx-series>
- One Google Pixel 5A 5G handset (phone). Be sure that the handset is unlocked.
 - https://www.gsmarena.com/google_pixel_5-10386.php
 - https://www.gsmarena.com/google_pixel_5a_5g-11059.php
 - <https://www.amazon.com/Google-Pixel-5G-Factory-Unlocked/dp/B09DV93S9K/>
- Two 5G SIM cards and one USB UICC/SIM card reader/writer.
 - <https://open-cells.com/index.php/sim-cards/>
- One Mini-Circuits 4-way DC-Pass, SMA, Power Splitter, 250 to 6000 MHz, 50Ω (ZN4PD1-63HP-S+).
 - <https://www.minicircuits.com/WebStore/Splitters.html>
 - <https://www.minicircuits.com/WebStore/dashboard.html?model=ZN4PD1-63HP-S%2B>

- Two Mini-Circuits, 2-way, DC-Pass SMA, Power Splitter, 500 to 5000 MHz, 50Ω (ZN2PD2-50-S+).
 - <https://www.minicircuits.com/WebStore/Splitters.html>
 - <https://www.minicircuits.com/WebStore/dashboard.html?model=ZN2PD2-50-S%2B>
- Four Mini-Circuits, VAT-10+, 10 dB Fixed Attenuator, DC to 6000 MHz, 50Ω, SMA.
 - <https://www.minicircuits.com/WebStore/dashboard.html?model=VAT-10%2B>
- Four Mini-Circuits, VAT-20+, 20 dB Fixed Attenuator, DC to 6000 MHz, 50Ω, SMA.
 - <https://www.minicircuits.com/WebStore/dashboard.html?model=VAT-20%2B>
- Four Mini-Circuits, VAT-30+, 30 dB Fixed Attenuator, DC to 6000 MHz, 50Ω, SMA.
 - <https://www.minicircuits.com/WebStore/dashboard.html?model=VAT-30%2B>
- Fourteen Coax SMA Cables, Mini-Circuits, SMA, Hand-Flex Interconnect, 18.0 GHz, 36 inches length (086-36SM+).
 - <https://www.minicircuits.com/WebStore/dashboard.html?model=086-36SM%2B>
 - <https://www.minicircuits.com/pdfs/086-36SM+.pdf>
- One NETGEAR GS108 8-Port Gigabit Ethernet Unmanaged Switch. See further details about this item in the Hardware Requirements section.
 - <https://www.netgear.com/business/wired/switches/unmanaged/gs108/>
 - <https://www.amazon.com/NETGEAR-Ethernet-Unmanaged-Lifetime-Protection/dp/B00MPVR50A/>
- Three adapters from USB 3.0 to 1 Gbps Ethernet. Any major reputable brand will work. Use either USB-A or USB-C connector as per the ports available on your host computer.
 - <https://www.amazon.com/Network-Adapter-CableCreation-Ethernet-Supporting/dp/B013G4C8RE/>
 - <https://www.amazon.com/Ethernet-Thunderbolt-Gigabit-Network-Compatible/dp/B07XTGKP5M/>

Hardware Requirements

Host Computers

Three host computers are needed, one for the gNB, one for the UE, and one for the CN, with the specifications discussed in this section. The requirements for the host computer running the CN are not as high as for the gNB and UE, but we recommend that all three host computers meet the requirements described here. We also strongly recommend that each of the gNB, UE, and CN be implemented on their own dedicated system. A single host computer should only run the gNB, or the UE, or the CN.

CPU

We recommend using an Intel Core i9 CPU, or an Intel Xeon CPU, 10th, 11th, or 12th Generation, with minimum clock speed of 4.0 GHz, and with minimum 10 physical cores. Examples of such a CPU would be the Intel i9-10940X CPU, which has 14 physical cores, 4.60 GHz clock speed, and is 10th generation, and the Intel i9-12900K CPU, which has 16 physical cores, 5.20 GHz clock speed, and is 12th generation, as well as the Intel Xeon Platinum 8351N. Be sure that the CPU has at least 40 PCIe lanes, or at least enough lanes to support any GPU and 10 Gbps Ethernet card that are being used. The system should ideally support PCIe Gen 4.

- <https://www.intel.com/content/www/us/en/products/sku/198014/intel-core-i910940x-xseries-processor-19-25m-cache-3-30-ghz/specifications.html>
- <https://ark.intel.com/content/www/us/en/ark/products/134599/intel-core-i912900k-processor-30m-cache-up-to-5-20-ghz.html>

Disk

We strongly recommend that only NVMe SSD disks are used. Many systems now use PCIe Gen-4, and we recommend using a PCIe Gen-4 NVMe SSD disk. We recommend the Samsung 980 PRO SSD drive. Do not SATA disks at all. Using a RAID configuration with multiple drives should not be necessary, although this can potentially be an option for further increasing performance and throughput.

- <https://www.samsung.com/us/computing/memory-storage/solid-state-drives/980-pro-pcie-4-0-nvme-ssd-1tb-mz-v8p1t0b-am/>
- <https://www.amazon.com/SAMSUNG-PCIe-Internal-Gaming-MZ-V8P1T0B/dp/B08GLX7TNT/>
- <https://www.tomshardware.com/reviews/samsung-980-pro-m-2-nvme-ssd-review>

Memory

The system should have either dual-channel or quad-channel DDR4 or DDR5 (preferred) memory, with the highest clock speed available. A minimum of 16 GB or 32 GB of memory should be sufficient. Larger amounts of memory should not be necessary, as no virtualization, RAM disk, or other large in-memory buffering is being used.

GPU

The GPU does not matter for the purposes of running UHD and OAI. If you might be doing some AI/ML processing in then GPU, then you may want to use a particular GPU. The OAI 5G stack does not currently leverage the GPU.

10 Gbps Ethernet network card

The gNB and UE system will need a two-port 10 Gbps Ethernet network card for connecting to the USRP radio. The CN system does not connect to any USRP, so it does not need a 10 Gbps Ethernet network card.

There are several cards that are relevant and that we recommend, depending on the specific use-case.

The Intel X710-DA2 is a solid network card, and works out-of-the-box with Ubuntu 20.04.4. However, it has some issues with DPDK. This reference design is not initially using DPDK, so these issues are not yet relevant. The card is widely available and relatively inexpensive. The X710-DA4 is a four-port version of the card.

Be sure that the computer's chassis can physically accommodate the network card.

- <https://ark.intel.com/content/www/us/en/ark/products/83964/intel-ethernet-converged-network-adapter-x710da2.html>
- <https://www.amazon.com/Intel-Ethernet-Converged-X710-DA2-X710DA2/dp/B00NJ3ZC26/>

- <https://www.cdw.com/product/intel-ethernet-converged-network-adapter-x710-da2-network-adapter-pcie/3473844>
- <https://www.newegg.com/intel-x710da2/p/N82E16833106253>

The Mellanox MCX4121A-ACAT ConnectX-4 is also a solid network card, and also works out-of-the-box with Ubuntu 20.04.4. Furthermore, it works well with DPDK.

- <https://store.mellanox.com/products/nvidia-mcx4121a-acat-connectx-4-lx-en-adapter-card-25gbe-dual-port-sfp28-pcie3-0-x8-rohs-r6.html>
- <https://www.mellanox.com/files/doc-2020/pb-connectx-4-lx-en-card.pdf>
- <https://store.nvidia.com/en-us/networking/store/product/MCX4121A-ACAT/nvidiamcx4121a-acatconnectx-4lxenadaptercard25gbe/>
- <https://www.amazon.com/Mellanox-ConnectX-4-MCX4121A-ACAT-25Gigabit-Ethernet/dp/B011HVAZ78/>
- <https://www.fs.com/products/119650.html>

QSFP28-to-SFP28 Breakout Cable for USRP X410

The USRP X410 only has a QSFP28 port, which is for 100 Gbps Ethernet. In order to connect the USRP X410 to the host computer via 10 Gbps Ethernet, a QSFP28-to-SFP28 breakout cable is needed. This cable will be required when using the USRP X410, and will connect directly to the 10 Gbps Ethernet cards. This cable is not needed for the USRP N300, N310, N320, N321.

It is certainly possible to directly connect the host computer to the 100 Gbps QSFP28 port of the USRP X410. In order to do this, a QSFP28 100 Gbps Ethernet card would be needed. We recommend the Mellanox/Nvidia MCX516A-CCAT (PCIe Gen3), and the Mellanox/Nvidia MCX516A-CDAT (PCIe Gen4). You will also need a QSFP28 cable. We recommend the Mellanox/Nvidia MCP1600-C003E26N, and the Mellanox/Nvidia MCP1600-C003E30L and MCP7F00-A001R30N. We also recommend the Intel E810 series network cards. There are both 100 Gbps Ethernet QSFP28 cards and 10 Gbps Ethernet SFP28/SFP+ cards. All these cards work well with Ubuntu 20.04 and DPDK.

However, in this release of the reference design, it is not necessary to use 100 Gbps Ethernet, which is only needed for supporting high aggregate data rates, such as for the larger 200 MHz and 400 MHz FR2 channel bandwidths, and/or for 2x2 MIMO configuration, both of which are not yet supported. For this release of the reference design, we recommend using the Intel X710-DA2 and the Mellanox MCX4121A-ACAT ConnectX-4 cards, and using dual 10 Gbps Ethernet connections.

- <https://store.nvidia.com/en-us/networking/store/product/MCP7F00-A003R26N/nvidiamcp7f00-a003r26ndacsplittercableethernet100gbeto4x25gbe3m/>
- <https://store.nvidia.com/en-us/networking/store/product/MCP7F00-A003R30L/nvidiamcp7f00-a003r30ldacsplittercableethernet100gbeto4x25gbe3m/>
- <https://store.mellanox.com/products/nvidia-mcp7f00-a001r30n-passive-copper-splitter-cable-ethernet-100gbe-to-4x25gbe-qsfp28-to-4xsfp28-1m-colored-30awg-ca-n.html>
- <https://store.mellanox.com/products/nvidia-mcx516a-ccat-connectx-5-en-adapter-card-100gbe-dual-port-qsfp28-pcie3-0-x16-tall-bracket-rohs-r6.html>

- <https://store.mellanox.com/products/nvidia-mcx516a-cdat-connectx-5-ex-en-adapter-card-100gbe-dual-port-qsfp28-pcie4-0-x16-tall-bracket-rohs-r6.html>
- <https://store.mellanox.com/products/nvidia-mcp1600-c003e26n-passive-copper-cable-ethernet-100gbe-qsfp28-3m-black-26awg-ca-n.html>
- <https://store.mellanox.com/products/nvidia-mcp1600-c003e30l-passive-copper-cable-ethernet-100gbe-qsfp28-3m-black-30awg-ca-l.html>
- <https://ark.intel.com/content/www/us/en/ark/products/series/184846/100gbe-intel-ethernet-network-adapter-e810.html>
- <https://www.intel.com/content/www/us/en/products/details/ethernet/800-network-adapters/e810-network-adapters/products.html>
- <https://www.intel.com/content/www/us/en/products/details/ethernet/800-network-adapters/e810-25gbe-network-adapters/products.html>

Example Systems

There are many vendors who sell host computers that meet these requirements. This reference design was implemented using System 76 Thelio Mira systems and Dell Precision 5820 systems. Both systems have flexible configuration options, and can be configured as described in this section.

- <https://system76.com/desktops/thelio-mira-b2/configure>
- <https://www.dell.com/en-us/work/shop/desktops-all-in-one-pcs/precision-5820-tower-workstation/spd/precision-5820-workstation>

USRP Devices

Two USRP devices are needed, one for the gNB, and one for the UE. The USRP may be any of USRP N300, N310, N320, N321, X410. The USRP devices can be mixed (i.e., the gNB could be implemented with a USRP X410, while the UE could be implemented with a USRP N310). All these USRP devices can support all the channel bandwidths in FR1, up to and including 100 MHz. For FR2, the USRP N320 can support the 50, 100, 200 MHz channel bandwidths, and the USRP X410 can support all the 50, 100, 200, 400 MHz channel bandwidths.

- <https://kb.ettus.com/N300/N310>
- <https://kb.ettus.com/N320/N321>
- <https://kb.ettus.com/X410>
- <https://www.ettus.com/all-products/usrp-n300/>
- <https://www.ettus.com/all-products/usrp-n310/>
- <https://www.ettus.com/all-products/usrp-n320/>
- <https://www.ettus.com/all-products/usrp-n321/>
- <https://www.ettus.com/all-products/usrp-x410/>

OctoClock-G

One OctoClock-G device is needed to synchronize the gNB USRP and the UE USRP. Ensure that device used is the "-G" version of the OctoClock, which contains an internal GPSDO module. This is only needed when the UE is implemented on a USRP device.

- <https://www.ettus.com/all-products/octoclock-g/>
- https://kb.ettus.com/OctoClock_CDA-2990

Host Computer for 5G Wireless Modem Module

One implementation of the UE is a 5G wireless modem module, such as the Quectel RM500Q-GL. The modem module requires a device driver and a connection to a host computer. It is possible to use one of the gNB, UE, CN host computers to also drive the modem module, but it is recommended to have a separate dedicated fourth host computer for this. This host computer need not be powerful or high-performance, and may run either Ubuntu 20.04 or Windows 10. It may be preferred to use Windows 10, as the Qualcomm drivers may work better on Windows than on Linux.

- <https://www.quectel.com/product/5g-rm500q-gl>
- <https://www.quectel.com/product/5g-rm50xq-series>

Software Requirements

Operating System

The required operating system for the gNB, UE, CN systems is Ubuntu 20.04.4. Be sure to use the Desktop image, not the Server image. It is also necessary to use the low-latency kernel on the gNB and UE systems, but not on the CN system. The kernel version should be 5.15 for Ubuntu 20.04.4. The "Installing and Configuring the UHD Software" section contains detailed information about what specific package dependencies need to be installed, and how to install the low-latency kernel. Either Kubuntu or Xubuntu may also be used, instead of Ubuntu. Do not run Ubuntu in a Virtual Machine (VM). Do not use any virtualization. Be sure to install Ubuntu on-the-metal.

The reference architecture will add support for Ubuntu 22.04.1 in the near future.

- <https://releases.ubuntu.com/20.04/>
- <https://xubuntu.org/download/>
- <https://kubuntu.org/getkubuntu/>
- <https://en.wikipedia.org/wiki/Ubuntu>
- <https://en.wikipedia.org/wiki/Xubuntu>
- <https://en.wikipedia.org/wiki/Kubuntu>

UHD

UHD is the open-source device driver for all USRP radios. The required version of UHD for this reference design is 4.2.0.0. The "Installing and Configuring the UHD Software" section contains detailed information about the installation and configuration procedure. The "Building and Installing the USRP Open-Source Toolchain (UHD and GNU Radio) on Linux" Application Note also contains details and thorough information about how to install and configure UHD.

We recommend that you build UHD from source code, and do not install it from a binary package. We also recommend that you build UHD first, before building and installing OAI, and that you do not build UHD using the OAI `build_oai` script. UHD is required on both the gNB system and the UE system, but it is not needed on the CN system.

- <https://github.com/EttusResearch/uhd>

OpenAirInterface (OAI)

The required version of OAI for this reference design is either 2022.w33 or the `devel` branch. We recommend that you build OAI from source code, using the `build_oai` script. The OAI software is required on the gNB, UE, and CN systems. The "Installing and Configuring the CN System", "Installing and Configuring the gNB System", and "Installing and Configuring the UE System" sections contains detailed information about the installation and configuration procedure for the OAI software. Be sure to build and install OAI only after building and installing UHD.

- <https://gitlab.eurecom.fr/oai/openairinterface5g>

DPDK

The Data Plane Development Kit (DPDK) is an open-source software project that provides a set of data plane libraries and network interface controller polling-mode drivers for offloading TCP packet processing from the operating system kernel to processes running in user-space. This offloading achieves higher computing efficiency and higher packet throughput than is possible using the interrupt-driven processing provided in the kernel. By putting the network interface driver in user space, avoiding context switches, and pinning I/O threads to cores, UHD and DPDK combine to largely prevent the latency spikes induced by the kernel scheduler, and the overall overhead for packet processing is reduced.

The current version of the reference design does not use DPDK, but it is expected that DPDK will be required in future versions of the reference architecture.

The "Getting Started with DPDK and UHD" Application Note contains detailed information about DPDK.

- <https://www.dpdk.org/>
- <https://github.com/DPDK/dpdk>
- https://en.wikipedia.org/wiki/Data_Plane_Development_Kit

Installing and Configuring the UHD Software

This section explains how to build and install UHD from source code. At the time of this writing, we recommend using UHD version 4.3.0.0.

Be sure to first install all the required dependencies, which can be done using the command listed below. You can run this command even if the dependencies are already installed and you just want to verify that.

```
sudo apt-get install autoconf automake build-essential ccache cmake cpufrequtils doxygen ethtool g++ git inetutils-tools libboost-all-dev libncurses5 libncurses5-dev libusb-1.0-0 libusb-1.0-0-dev libusb-dev
```

First start by creating a working folder to store Git repositories.

```
cd $HOME/git
mkdir $HOME/git
```

Next, clone the UHD repository on GitHub in the working folder.

```
cd $HOME/git
git clone http://github.com/EttusResearch/uhd.git
```

Then, create a build folder, and select UHD version 4.3.0.0.

```
cd uhd/host
mkdir build
cd build
git checkout v4.3.0.0
```

Then, build UHD, using the default settings, and install it to the default location.

```
cmake ../
make -j4
sudo make install
sudo ldconfig
```

Finally, add the following lines the end of your \$HOME/.bashrc file.

```
export PYTHONPATH=/usr/local/lib/python3/dist-packages:/usr/local/lib/python3.7/site-packages:/usr/local/lib/python3/dist-packages:$PYTHONPATH
export LD_LIBRARY_PATH=/usr/local/lib:$LD_LIBRARY_PATH
```

Verify that UHD was correctly installed. Check the version number, and be sure that the uhd_find_devices utility program run.

```
uhd_config_info --print-all
uhd_find_devices
uhd_usrp_probe
```

Installing and Configuring the USRP Radio

The USRP N300, N310, N320, N321, X410 can all be used as the gNB and the UE.

For the USRP N300 and N310

See the article [USRP N300/N310/N320/N321 Getting Started Guide](#) for information about how to set up and configure your USRP N300 and N310 for use with UHD and OAI.

The USRP N300 and N310 support all the channel bandwidths in FR1.

For the USRP N320 and N321

See the article [USRP N300/N310/N320/N321 Getting Started Guide](#) for information about how to set up and configure your USRP N320 and N321 for use with UHD and OAI.

The USRP N320 and N321 support all the channel bandwidths in FR1, and all but the 400 MHz channel bandwidth in FR2.

For the USRP X410

See the article [USRP X410 Getting Started Guide](#) for information about how to set up and configure your USRP X410 for use with UHD and OAI.

The USRP X410 supports all the channel bandwidths both in FR1 and FR2.

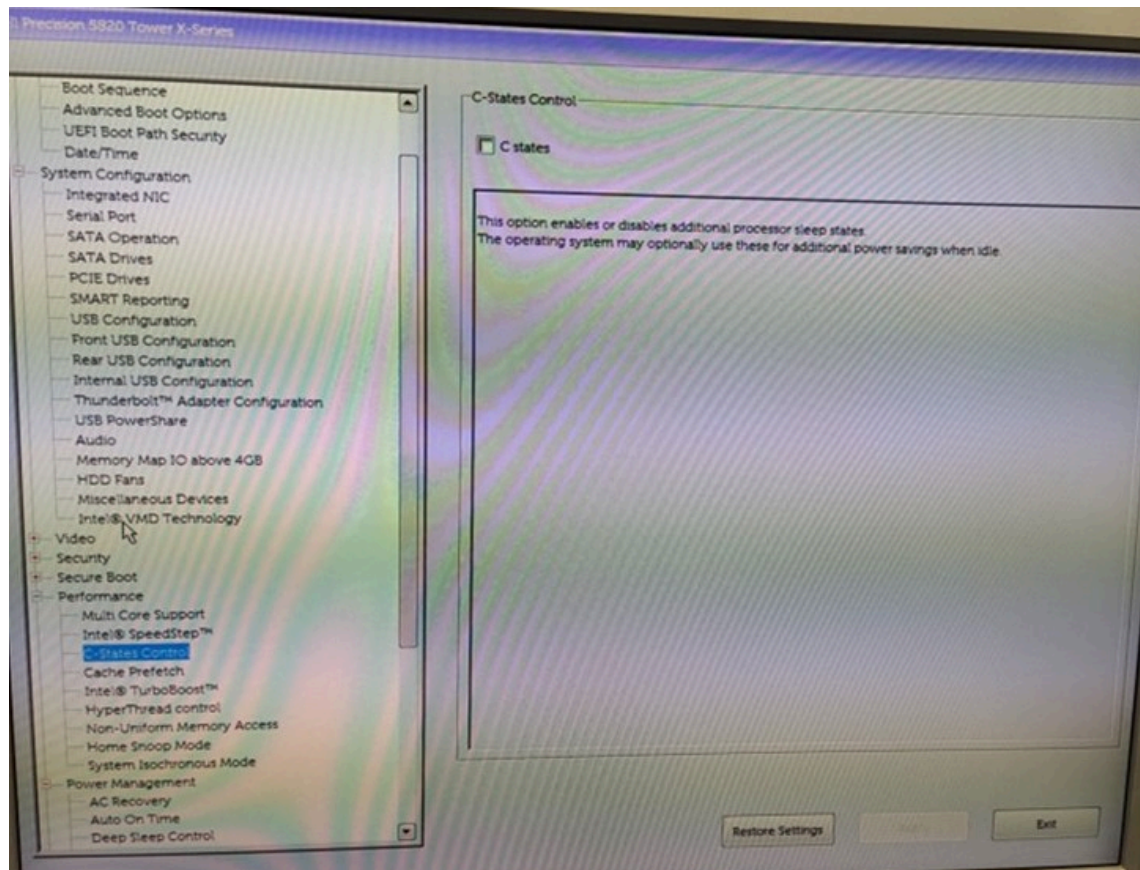
Configuring the Ubuntu Linux Operating System

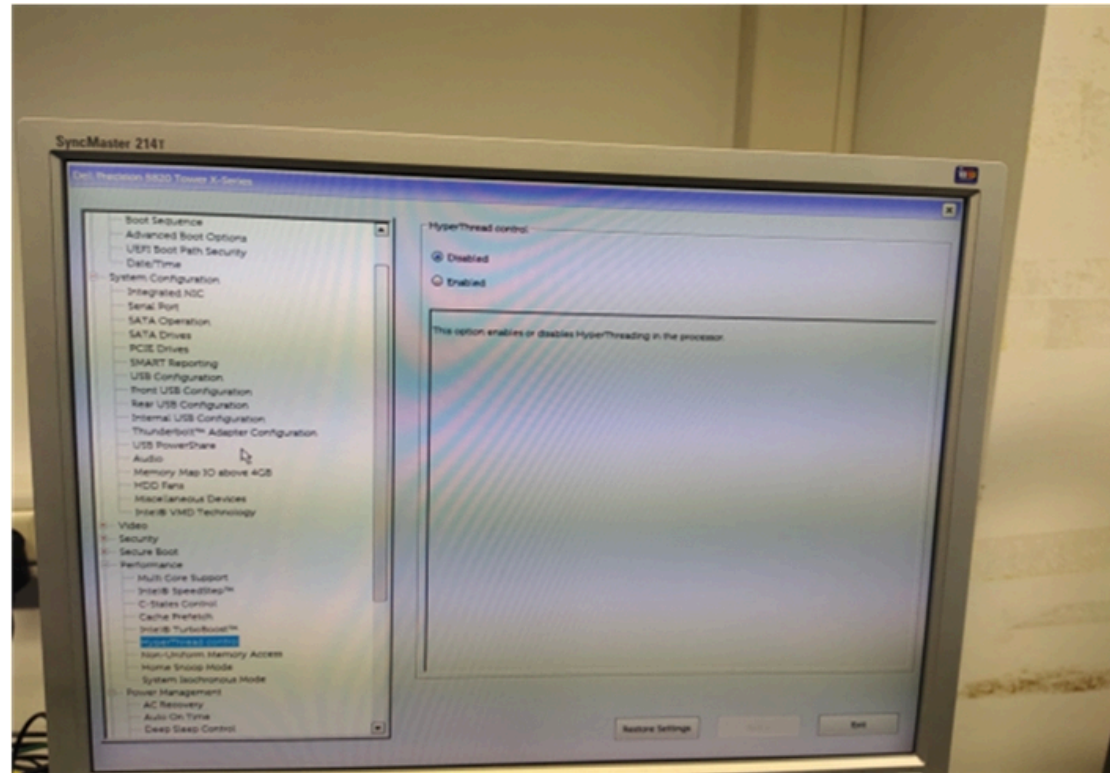
See the article [USRP Host Performance Tuning Tips and Tricks](#) for information about specific settings and configuration procedures needed to enable optimal system performance. Specifically, it is necessary to set the CPU governors, enable the thread priority scheduling, set the socket buffer sizes, set the Ethernet MTU values, and set the network card ring buffer sizes.

The use of the Data Plane Development Kit (DPDK) should not be necessary for running any of the FR1 channel bandwidths. At the time of this writing, DPDK is not used in this reference architecture.

Configuring the BIOS for gNB and UE Systems

On the gNB system, and on the UE system, if the UE being used is a USRP radio, there are several specific settings that need to be made. The hyperthreading, CPU frequency control, C-states, P-states, and any other power management should all be disabled. Each BIOS will have a different way to do this. The two screenshots below show where in the BIOS menu to disable C-states and to disable Hyperthreading. Once these options are set in the BIOS, reboot the system.





Installing, Configuring, and Running the CN System

This section explains the deployment of the OAI 5G CN system on Ubuntu 20.04 with a generic kernel. The deployment is possible either using docker-compose or Helm Chart. We recommend using docker-compose.

The 5G CN deployment is possible in various forms using docker-compose or Helm Chart.

- Using docker-compose, perform a minimalist deployment
- Using docker-compose, perform a basic deployment
- Using docker-compose, perform a basic-vpp deployment with VPP implementation of UPF
- Using docker-compose, perform a basic deployment with static UE IP address allocation
- Using Helm Chart, perform a basic deployment
- Using docker-compose, doing network slicing

This Application Note explains only the minimalist deployment using docker-compose.

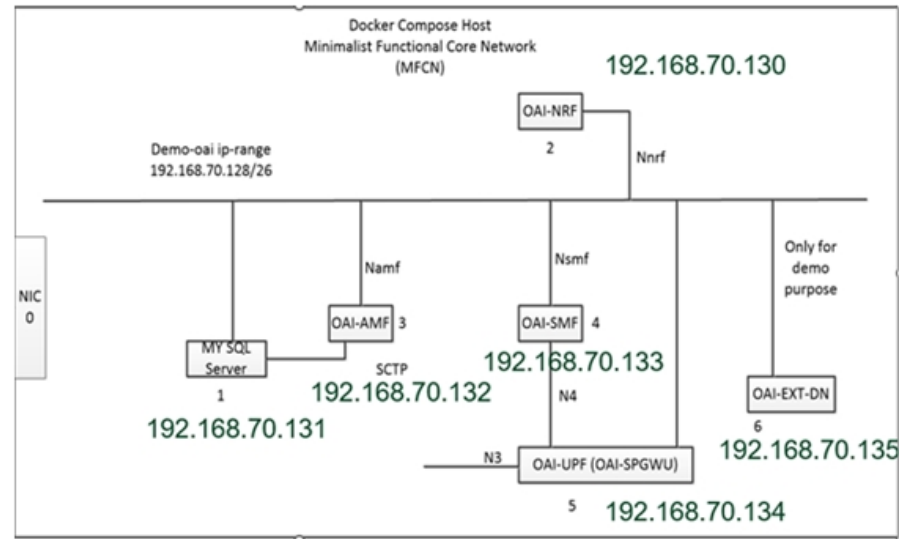
The minimalist deployment can be performed in two scenarios:

- Scenario 1: AMF, SMF, UPF (SPGWU), NRF, MYSQL

■ Scenario 2: AMF, SMF, UPF (SPGWU), MYSQL

This Application Note only discusses Scenario 1.

The diagram below shows the layout and architecture of the various Docker containers running on the CN machine, along with the IP address of each container.



Prerequisites for the Scenario 1 Minimalist Deployment

Verify that you are running docker-compose version 1.25 or higher.

```
dpkg --get | grep docker
```

Verify that you are running Python version 3.6 or higher.

```
python3 --version
```

Note that you should add your username to the `docker` group so that you can run Docker operations without needing root privileges.

To add your username to the `docker` group, use the command below.

```
sudo usermod -a -G docker yourusername
```

In order to pull the Docker images for the different network functions of the 5G CN, you need to have an account on docker-hub. Use this link to create an account.

Pull Base Images

We need to pull two base Docker images `ubuntu:bionic` and `mysql:5.7`.

Log in with your Docker Hub credentials, and push and pull images from Docker Hub.

```
docker login
docker pull ubuntu:bionic
docker pull mysql:5.7
docker logout
```

Be sure to set the following network configuration settings. You must run these commands every time you restart the CN machine, as they will not persist across a reboot.

```
sudo sysctl net.ipv4.conf.all.forwarding=1
sudo iptables -P FORWARD ACCEPT
```

Pulling the images from Docker Hub

The images are hosted under the OAI account `oaisoftwarealliance`.

You may need to login to Docker Hub.

```
docker login
```

Pull the images listed below.

```
docker pull rdefosseoai/oai-amf:latest
docker pull rdefosseoai/oai-nrf:latest
docker pull rdefosseoai/oai-spgwu-tiny:latest
docker pull rdefosseoai/oai-smf:latest
docker pull rdefosseoai/oai-udr:latest
docker pull rdefosseoai/oai-udm:latest
docker pull rdefosseoai/oai-ausf:latest
docker pull rdefosseoai/oai-upf-vpp:latest
docker pull rdefosseoai/oai-nssf:latest
```

Re-tag the images so that the docker-compose files for the tutorial work.

```
docker image tag rdefosseoai/oai-amf:latest oai-amf:latest
docker image tag rdefosseoai/oai-nrf:latest oai-nrf:latest
docker image tag rdefosseoai/oai-smf:latest oai-smf:latest
docker image tag rdefosseoai/oai-spgwu-tiny:latest oai-spgwu-tiny:latest
docker image tag rdefosseoai/oai-udr:latest oai-udr:latest
docker image tag rdefosseoai/oai-udm:latest oai-udm:latest
docker image tag rdefosseoai/oai-ausf:latest oai-ausf:latest
docker image tag rdefosseoai/oai-upf-vpp:latest oai-upf-vpp:latest
docker image tag rdefosseoai/oai-nssf:latest oai-nssf:latest
```

Finally, you may logoff. Your token is stored in plain-text.


```
docker logout
```

Synchronizing the installed images

Clone the Git repository for the Core Network, and checkout the v1.3.0 tag.

```
git clone --branch v1.3.0 https://gitlab.eurecom.fr/oai/cn5g/oai-cn5g-fed.git
```

You may also do this in two discrete steps.

```
git clone https://gitlab.eurecom.fr/oai/cn5g/oai-cn5g-fed.git
git checkout v1.3.0
```

Next, go into the top-level folder in the repository.

```
cd oai-cn5g-fed
```

Next, synchronize all the Git submodules.

```
./scripts/syncComponents.sh
```

```
-----
OAI-NRF      component branch : master
OAI-AMF      component branch : master
OAI-SMF      component branch : master
OAI-SPGW-U   component branch : master
OAI-AUSF     component branch : master
OAI-UDM      component branch : master
OAI-UDR      component branch : master
OAI-UPF-VPP  component branch : master
OAI-NSSF     component branch : master
-----
```

```
git submodule deinit --all --force
git submodule init
git submodule update
```

Configure the Containers

Configure the Core Network by editing the `docker-compose-mini-nrf.yaml` file and specifying the proper PLMN, TAC, Operator Key, and DNN, according to the gNB and the UE being used.

If you are using the v1.3.0 tag for the CN code, then specify the PLMN, TAC, and Operator Key in the `amf.conf` file, according to the gNB and the UE being used. If you are using the newer v1.3.0 tag for the CN code, then do not do this.

User subscription information should be present in the MySQL database before trying to connect the UE. This can be done by adding the UE information into the `oai_db1.sql` file. Adjust the values shown below with your actual values.

```
INSERT INTO users VALUES
(imsi,msisdn,imei,NULL,'PURGED',50,40000000,100000000,47,0000000000,1,key,0,0,0x40,'ebd07771ace8677a',opc);
```

Deploy the containers

The containers must be deployed in a strict order for AMF, SMF, and UPF registration with NRF. The data flow sequence must be from the MySQL database, to OAI-NRF, to OAI-AMF, to OAI-SMF, to OAI-UPF.

Installing docker-compose and Wireshark

Install docker-compose onto the Core Network system. The link below provides detailed instructions.

<https://www.digitalocean.com/community/tutorials/how-to-install-and-use-docker-compose-on-ubuntu-20-04>

Install Wireshark with the commands listed below.

```
sudo add-apt-repository ppa:wireshark-dev/stable
sudo apt update
sudo apt install wireshark
```

Check the Wireshark version, and confirm that it is at least version 3.4.7.

```
wireshark --version
```

Invoking the Core Network

The Core Network is invoked using a Python script, which is a wrapper for docker-compose and other Docker commands. The script informs the user when the Core Network is correctly configured by checking the health status of containers and checking the connectivity between different Core Network components. Run the commands below.

```
cd oai-cn5g-fed/docker-compose
sudo python3 ./core-network.py --type start-mini --fqdn no --scenario 1
```

After running the command, you should see the output listed below.

```
root:DEBUG: Starting 5gcn components... Please wait...
Creating oai-nrf ... done
Creating mysql ... done
Creating oai-amf ... done
Creating oai-smf ... done
Creating oai-spgwu ... done
Creating oai-ext-dn ... done
[2021-09-14 16:44:10,098] root:DEBUG: OAI 5G Core network started, checking the health status of the containers... takes few secs...
[2021-09-14 16:44:47,025] root:DEBUG: All components are healthy, please see below for more details...
Name          Command          State          Ports
-----
mysql         docker-entrypoint.sh mysqld    Up (healthy)   3306/tcp, 33060/tcp
oai-amf       /bin/bash /openair-amf/bin ... Up (healthy)   38412/sctp, 80/tcp, 9090/tcp
oai-ext-dn    /bin/bash -c apt update; ... Up
oai-nrf       /bin/bash /openair-nrf/bin ... Up (healthy)   80/tcp, 9090/tcp
```

```

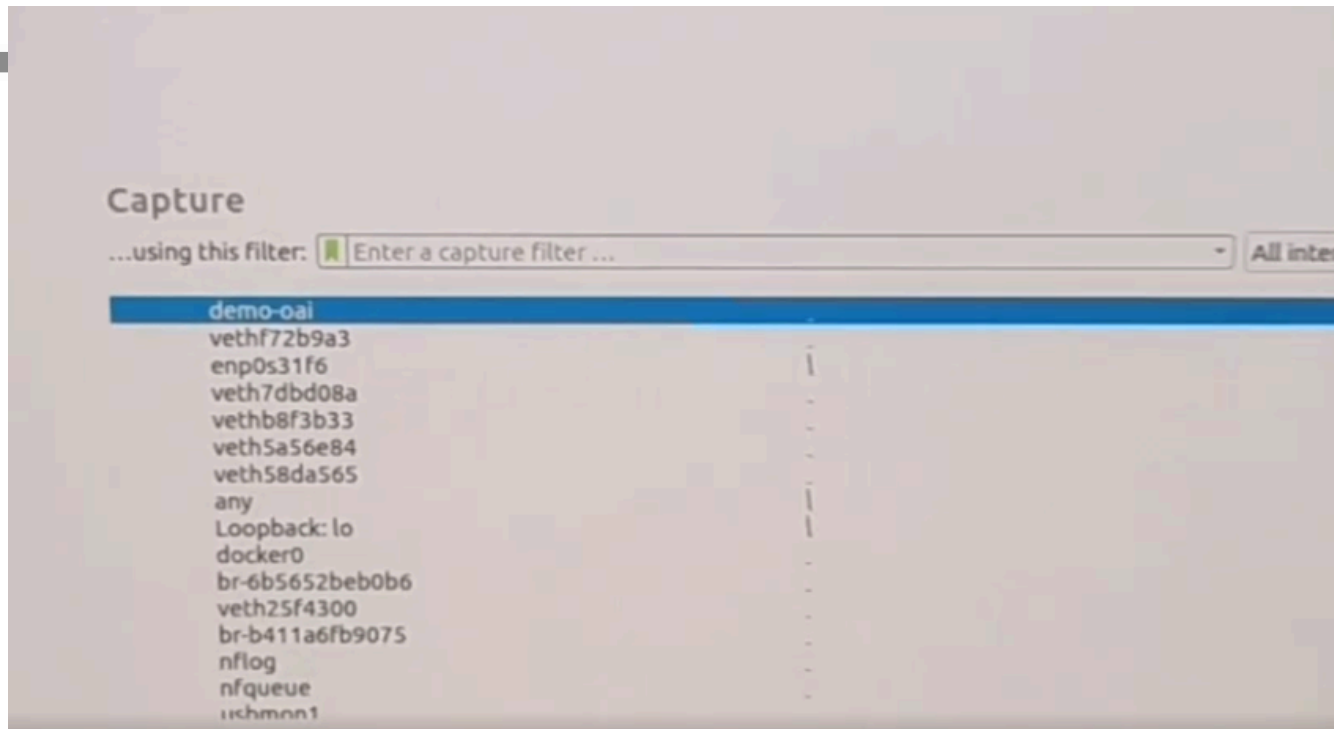
oai-smf      /bin/bash /openair-smf/bin ... Up (healthy) 80/tcp, 8805/udp, 9090/tcp
oai-spgwu    /openair-spgwu-tiny/bin/en ... Up (healthy) 2152/udp, 8805/udp
[2021-09-14 16:44:47,025] root:DEBUG: Checking if the containers are configured....
[2021-09-14 16:44:47,025] root:DEBUG: Checking if SMF and UPF registered with nrf core network....
[2021-09-14 16:44:47,059] root:DEBUG: For example: oai-smf Registration with oai-nrf can be checked on this url /nnrf-nfm/v1/nf-instances?nf-type="SMF" {"_links":{"item":[{"href":"192.168.70.133"}],"se
[2021-09-14 16:44:47,059] root:DEBUG: SMF and UPF are registered to NRF....
[2021-09-14 16:44:47,059] root:DEBUG: Checking if SMF is able to connect with UPF....
[2021-09-14 16:44:47,176] root:DEBUG: UPF receiving heathbeats from SMF....
[2021-09-14 16:44:47,176] root:DEBUG: OAI 5G Core network is configured and healthy....

```

After launching the OAI 5G Core Network, run Wireshark from another terminal.

```
sudo wireshark
```

Once Wireshark has launched, you should see the `demo-oai` network interface listed. Open the `demo-oai` network interface, and confirm that all the packets exchanged between the different containers such as NRF, AMF, SMF, UPF are shown.



The `demo-oai` network interface can also be created manually. Since this is not the default behavior, you would need to edit the `docker-compose` file. The bottom section of the `docker-compose-mininrf.yaml` should be configured as shown below.

```

networks:
  public_net:
    external:
      name: demo-oai-public-net
  # public_net:
  #   driver: bridge

```

```
# name: demo-oai-public-net
# ipam:
#   config:
#     - subnet: 192.168.70.128/26
# driver_opts:
#   com.docker.network.bridge.name: "demo-oai"
```

The `docker-compose-host` machine needs to be configured with the `demo-oai` network interface before deploying the core network components. This is needed in order to capture the initial message exchange between the SMF-to-NRF-to-UPF.

```
(docker-compose-host)v$ docker network create \
--driver=bridge \
--subnet=192.168.70.128/26 \
-o "com.docker.network.bridge.name="demo-oai" \
demo-oai-public-net
455631b3749ccd6f10a366cd1c49d5a66cf976d17688425d5d88a1e54049bc5
(docker-compose-host)$ ifconfig demo-oai
demo-oai: flags=4099<UP,BROADCAST,MULTICAST> mtu 1500
    inet 192.168.70.129 netmask 255.255.255.192 broadcast 192.168.70.191
    RX packets 0 bytes 0 (0.0 B)
    RX errors 0 dropped 0 overruns 0 frame 0
    TX packets 0 bytes 0 (0.0 B)
    TX errors 0 dropped 0 overruns 0 carrier 0 collisions 0
(docker-compose-host)$ docker network ls
NETWORK ID          NAME                DRIVER              SCOPE
d2d34e05bb2d        bridge              bridge              local
455631b3749c        demo-oai-public-net bridge              local
```

We will next create a bridge automatically. The bridge can be automatically created using the `docker-compose` file, if there is no need to capture initial packets. This is the default version in the `docker-compose-mini-nrf.yaml` file. The bottom section should be configured as shown below.

```
networks:
# public_net:
#   external:
#   name: demo-oai-public-net
public_net:
  driver: bridge
  name: demo-oai-public-net
  ipam:
    config:
      - subnet: 192.168.70.128/26
  driver_opts:
    com.docker.network.bridge.name: "demo-oai"
```

The screenshots listed below show the Wireshark packet captures for various components when the bridge is built manually.

Showing the NRF and AMF:

3	2.959854473	192.168.70.132	192.168.70.130	TCP	74 57964 → 80 [SYN] Seq=0 Win=64240 Len=0 MSS=1460 SACK_PERM=1 TSval=2040969696 TSecr=0 WS=128
4	2.959876019	192.168.70.130	192.168.70.132	TCP	74 80 → 57964 [SYN, ACK] Seq=0 Ack=1 Win=65160 Len=0 MSS=1460 SACK_PERM=1 TSval=2466639410 TSecr=26

Showing the NRF and SMF:

13	4.176452769	192.168.70.133	192.168.70.130	TCP	74 59742 → 80 [SYN] Seq=0 Win=64240 Len=0 MSS=1460 SACK_PERM=1 TSval=1200628820 TSecr=0 WS=128
14	4.176473640	192.168.70.130	192.168.70.133	TCP	74 80 → 59742 [SYN, ACK] Seq=0 Ack=1 Win=65160 Len=0 MSS=1460 SACK_PERM=1 TSval=1866640461 TSecr=12

Showing the SMF and UPF:

33	5.958342193	192.168.70.134	192.168.70.133	PF-CP	79 PF-CP Association Setup Request
34	5.964381059	192.168.70.133	192.168.70.134	PF-CP	77 PF-CP Association Setup Response

Showing the NRF and UPF:

35	6.018142673	192.168.70.134	192.168.70.130	TCP	74	48226 → 80 [SYN] Seq=0 Win=64240 Len=0 MSS=1460 SACK_PERM=1 TSval=1520545755 TSecr=0 WS=128
36	6.018164174	192.168.70.130	192.168.70.134	TCP	74	80 → 48226 [SYN, ACK] Seq=0 Ack=1 Win=65160 Len=0 MSS=1460 SACK_PERM=1 TSval=1908952015 TSecr=152

Showing the SMF request to NRF for subscribing UPF registration/deregistration events:

16	5.254114218	192.168.70.133	192.168.70.130	HTTP/JSON	444	POST /nnrf-nfm/v1/subscriptions HTTP/1.1 , JavaScript Object Notation (application/json)
----	-------------	----------------	----------------	-----------	-----	--

Showing the SMF registration with NRF for the PUT request:

26	5.266108102	192.168.70.133	192.168.70.130	HTTP/JSON	982	PUT /nnrf-nfm/v1/nf-instances/5bbdb05e-94bc-4dbc-b479-84b82bfc873d HTTP/1.1 , JavaScript 0
----	-------------	----------------	----------------	-----------	-----	--

Showing the UPF registration with NRF for the PUT request:

38	7.285212938	192.168.70.134	192.168.70.130	HTTP/JSON	596	PUT /nnrf-nfm/v1/nf-instances/62daccb7-5b2c-4d53-89dc-f1292d8e5bf1 HTTP/1.1 , JavaScript 0
----	-------------	----------------	----------------	-----------	-----	--

Showing the NRF notification to SMF for UPF registration for the POST request:

43	7.285636623	192.168.70.130	192.168.70.133	HTTP/JSON	707	POST /nsmf-nfstatus-notify/v1/subscriptions HTTP/1.1 , JavaScript Object Notation (applic
----	-------------	----------------	----------------	-----------	-----	---

Showing the SMF-to-UPF PFCP association setup request-and-response:

45	7.295097217	192.168.70.133	192.168.70.134	PFCP	72	PFCP Association Setup Request
46	7.295283861	192.168.70.134	192.168.70.133	PFCP	84	PFCP Association Setup Response

These Wireshark packet captures are only visible if you create the `demo-oai` bridge manually. If the bridge is built automatically, then you will not observe these Wireshark packet captures.

Stopping the Core Network

In order to halt the operation of the Core Network, run the commands listed below.

```
cd oai-cn5g-fed/docker-compose
sudo python3 ./core-network.py --type stop-mini --fqdn no --scenario 1
```

Installing, Configuring, and Running the gNB System

Before installing and configuring the gNB system, be sure that you first have configured the system BIOS, implemented the Linux performance tuning settings, and installed UHD.

Building and installing the gNB software

The commands listed below build and install the gNB software from source code using the OAI Git repository.

```
git clone https://gitlab.eurecom.fr/oai/openairinterface5g.git
cd openairinterface5g
git checkout 2022.w33
source oaienv
cd cmake_targets
```

Confirm that you are using the correct branch and commit hash. Run the command listed below, and verify that the branch is `2022.w33` and that the commit hash is `ad8381a66bb67d6ef7fa94c9a6ae6c66f3ae84b8`.

```
git status
```

Edit the `build_oai` script, and comment out the lines shown below, by adding a hash mark `#` at the beginning of each line.

```
if [ "$HW" == "OAI_USRP" ] ; then
  echo_info "installing packages for USRP support"
  #check_install_usrp_uhd_driver
  #if [ ! "$DISABLE_HARDWARE_DEPENDENCY" == "True" ]; then
  #  install_usrp_uhd_driver $UHD_IMAGES_DIR
  #fi
fi
```

For the very first time that you build the gNB software, use the command listed below, which includes the `-I` option, which installs the package dependencies for the gNB software.

```
./build_oai -I --w USRP
```

For successive builds, use the command listed below, which omits the `-I` option.

```
./build_oai --gNB --w USRP
```

Editing the gNB configuration file

Once the gNB software is built and installed, there are specific settings that need to be made in the gNB configuration file before we can run the gNB software. The folder `openairinterface5g/ci_scripts/conf_files` contains various configuration files. For this Application Note, we will use the configuration file `band78.sa.fr1.106PRB.usrpn310.conf`. In this file, change the parameters in the PLMN section. Ensure that the PLMN configuration values are the same as the values used for the CN system, specifically `tracking_area_code`, `mcc`, `mnc`, `sst`, and `sd`.

```

gNB_name = "gNB-OAI";
min_rxtxttime_pdsch = 6;

// Tracking area code, 0x0000 and 0xfffe are reserved values
tracking_area_code = 40960;

plmn_list = ({
    mcc = 208;
    mnc = 92;
    mnc_length = 2;
    snssailist = (
        {
            sst = 1;
            sd = 0x00007b; // 0 false, else true
        },
        {
            sst = 1;
            sd = 0x00000c; // 0 false, else true
        }
    );
});

nr_cellid = 12345678L

```

Specifying the AMF IP address

The correct IP address for the AMF needs to be defined in the configuration file, as shown below. In the configuration file, in the `AMF parameters` section, in the `ipv4` field, add the IP address of the AMF Docker container. In this reference architecture, it is 192.168.70.132.

```

////////// AMF parameters:
amf_ip_address = ( { ipv4      = "192.168.70.132";
                     ipv6      = "192:168:30::17";
                     active    = "yes";
                     preference = "ipv4";

```

Specifying the gNB IP address

The correct IP address for the gNB needs to be defined in the configuration file, as shown below. In the configuration file, in the `NETWORK_INTERFACES` section, add the IP address of the gNB system to the `GNB_IPV4_ADDRESS_FOR_NG_AMF` and the `GNB_IPV4_ADDRESS_FOR_NGU` fields. In this reference architecture, it is 10.89.14.37.

```

NETWORK_INTERFACES :
{
    GNB_INTERFACE_NAME_FOR_NG_AMF      = "demo-oai";
    GNB_IPV4_ADDRESS_FOR_NG_AMF        = "10.89.14.37";
    GNB_INTERFACE_NAME_FOR_NGU         = "demo-oai";
    GNB_IPV4_ADDRESS_FOR_NGU           = "10.89.14.37";
    GNB_PORT_FOR_S1U                    = 2152; # Spec 2152
};

```

Specifying the USRP IP address

The correct IP address for the USRP needs to be defined in the configuration file, as shown below. In the configuration file, in the `RU` section, in the `sdr_addrs` field, we need to specify the device arguments for the USRP, which includes the type of the USRP (`type`), the management IP address (`mgmt_addr`), the primary streaming IP address (`addr`), the secondary streaming IP address (`second_addr`), the clocking source (`clock_source`), and the timing source (`time_source`). In this reference architecture, we use the device argument string listed below.

```
sdr_addrs="type=x4xx,mgmt_addr=192.168.10.2,addr=192.168.10.2,second_addr=192.168.20.2,clock_source=external,time_source=external"
```

The `mgmt_addr`, `addr`, and `second_addr` should be defined according to the configuration of your USRP device. For the `clock_source` and the `time_source`, the values can be `internal`, `external`, or `gpsdo`. In this reference architecture, an OctoClock-G is connected to the USRP, so we use the value of `external` for both the clocking source and the timing source.

Adding a static route to the CN system

To enable communication between the gNB and CN machine, a static route must be added to the gNB machine. Note that this added route is not permanent, and when the system is restarted, the static route will need to be added again. The command listed below will add the static route.

```
sudo ip route add 192.168.70.128/26 via 10.89.14.119 dev eno1
```

In this command, the IP address `192.168.70.128/26` is for the `demo-oai` network bridge created when the CN is invoked, and the IP address `10.89.14.119` is for the CN machine, and the `eno1` Ethernet interface is the port on the gNB machine connected to the CN machine.

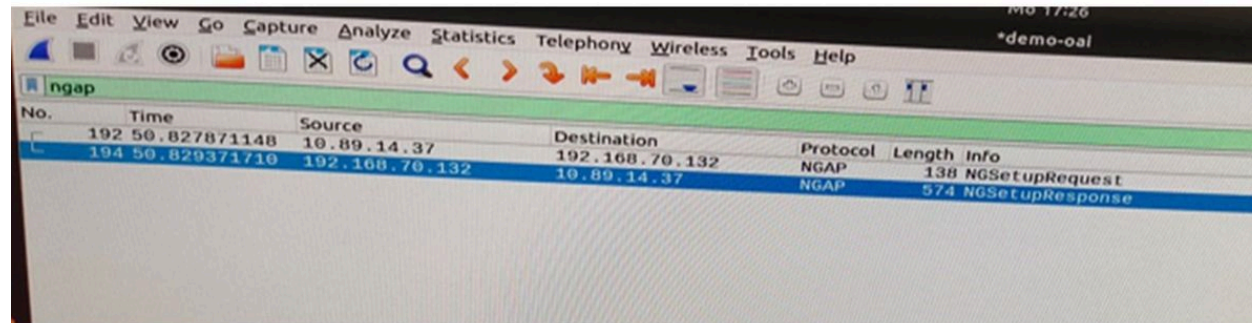
On your machine, the Ethernet interface name will likely be different, but you can use the same IP address for the CN machine, and the same static IP address for the CN machine, as used in this reference architecture.

Invoking the gNB

In order to invoke the gNB, we first need to copy the edited gNB configuration file from the folder `openairinterface5g/ci_scripts/conf_files` to the folder `openairinterface5g/targets/PROJECTS/GENERIC-NR-5G/CONF`. Then, the command listed below will invoke the gNB.

```
sudo ./nr-softmodem -O ../../../../targets/PROJECTS/GENERIC-NR-5G/CONF/gnb.band78.sa.fr1.106PRB.usrpn310.conf --sa --usrp-tx-thread-config 1 --thread-pool 0,2,4,6
```


Launch Wireshark, select the Ethernet interface connected to the CN machine, and watch for NGAP packets. As soon as the gNB is launched, the CN and gNB will exchange NGAP setup request and response messages. In these messages, the gNB and CN check the MCC, MNC and TAC parameters. If these values are identical on both the gNB machine and the CN machine, then the NGAP setup request and response will be successful.

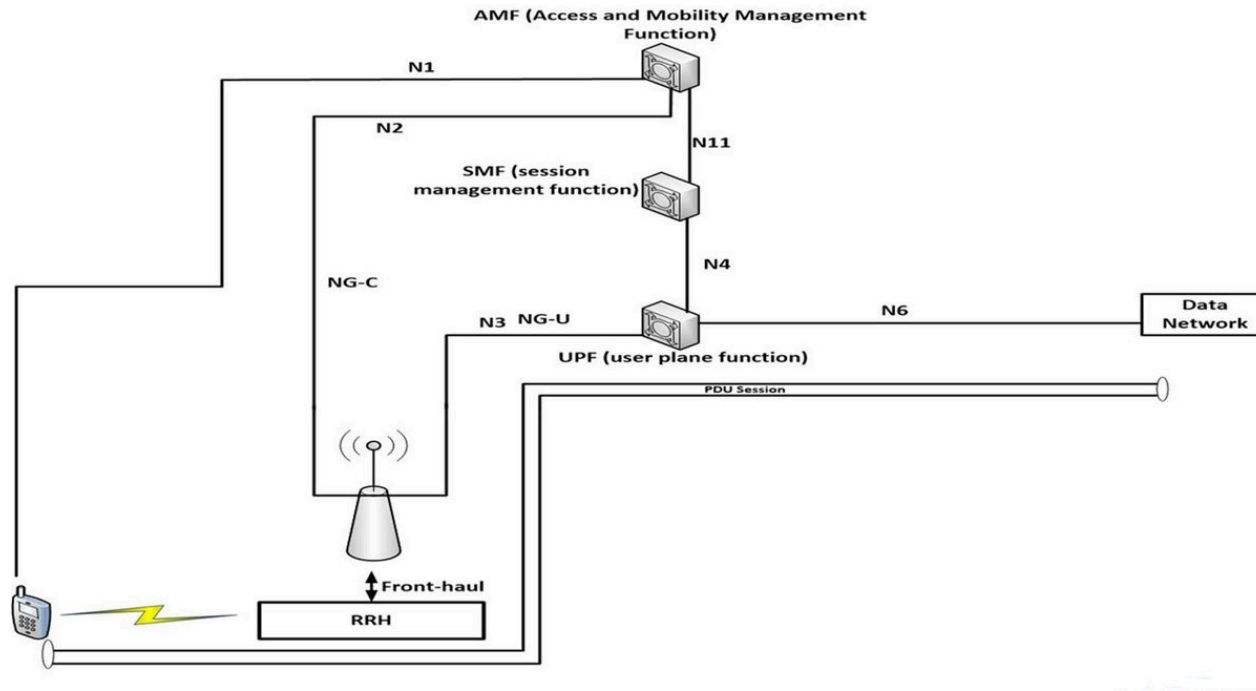


The image shows a Wireshark packet capture window with the filter 'ngap' applied. The packet list shows two packets: packet 192 is an NGAP NGSetupRequest (138 bytes) from 10.89.14.37 to 192.168.70.132, and packet 194 is an NGAP NGSetupResponse (574 bytes) from 192.168.70.132 to 10.89.14.37. The packet details pane for packet 194 shows the 'NGAP' protocol and 'NGSetupResponse' message.

No.	Time	Source	Destination	Protocol	Length	Info
192	50.827871148	10.89.14.37	192.168.70.132	NGAP	138	NGSetupRequest
194	50.829371710	192.168.70.132	10.89.14.37	NGAP	574	NGSetupResponse

Interfaces Between gNB and Core Network

When the gNB is invoked, the N2 and N3 interfaces will be created. The N2 interface supports the NGAP protocol, and the N3 interface supports the GTP protocol. The N1 interface is created when UE attaches to the network and supports the NAS protocol.



Testing Connectivity Between gNB and CN

Once both the gNB and the CN machines are up-and-running, test the connectivity between the two systems by pinging the AMF in the CN machine from the gNB machine. On the gNB machine, run the command listed below.

```
ping 192.168.70.132
```

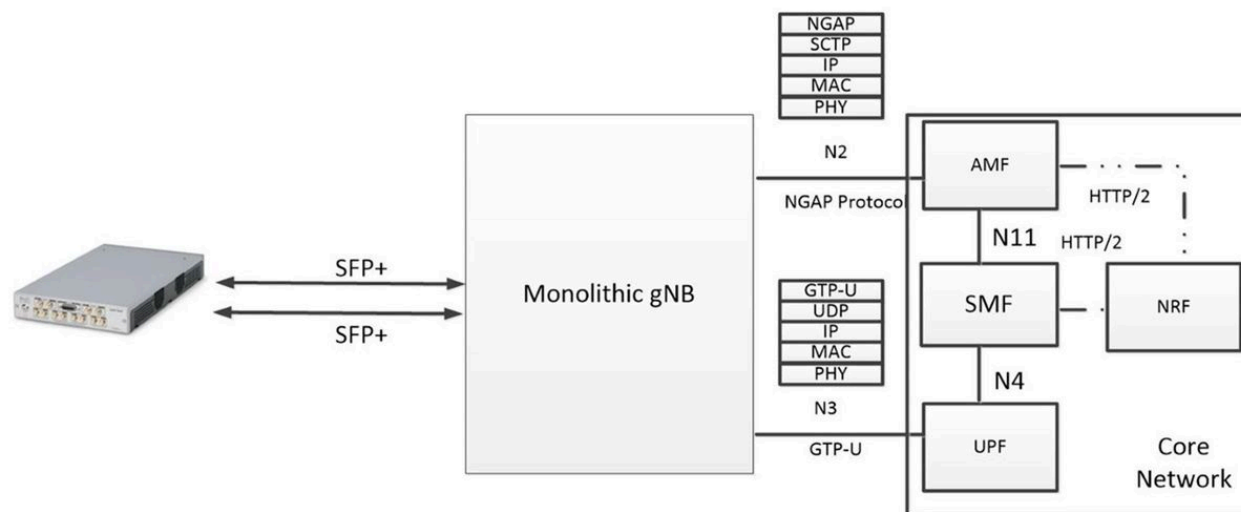
If the ping fails, then it may be due to the firewall settings. On the CN machine, run the commands listed below to configure the firewall.

```
sysctl net.ipv4.conf.all.forwarding=1
sudo iptables -P FORWARD ACCEPT
```

After running these commands on the CN machine, run this command on the gNB machine to add a route from the gNB machine to the CN machine. You will likely need to replace the Ethernet interface name `eno1` with the correct interface name on your gNB machine.

```
sudo ip route add 192.168.70.128/26 via 10.89.14.6 dev eno1
```

The IP address `192.168.70.128/26` is for the `demo-oai` interface, and `10.89.14.6` is the IP address of the CN machine, and `eno1` is the Ethernet interface name on the gNB machine.



Wireshark

File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help

sctp

No.	Time	Source	Destination	Protocol	Length	Info
166	10.456720134	10.89.14.37	192.168.70.132	SCTP	106	INIT
167	10.456894742	192.168.70.132	10.89.14.37	SCTP	338	INIT_ACK
168	10.456914129	10.89.14.37	192.168.70.132	SCTP	310	COOKIE_ECHO
169	10.457054530	192.168.70.132	10.89.14.37	SCTP	60	COOKIE_ACK
170	10.457517584	10.89.14.37	192.168.70.132	SCTP	138	DATA
171	10.457636391	192.168.70.132	10.89.14.37	SCTP	62	SACK
172	10.458823479	192.168.70.132	10.89.14.37	SCTP	206	DATA
173	10.458829242	10.89.14.37	192.168.70.132	SCTP	62	SACK
400	42.743523364	10.89.14.37	192.168.70.132	SCTP	98	HEARTBEAT
401	42.743654850	192.168.70.132	10.89.14.37	SCTP	98	HEARTBEAT_ACK
407	44.397879797	192.168.70.132	10.89.14.37	SCTP	98	HEARTBEAT
408	44.397883922	10.89.14.37	192.168.70.132	SCTP	98	HEARTBEAT_ACK
658	74.487523904	10.89.14.37	192.168.70.132	SCTP	98	HEARTBEAT
659	74.487648170	192.168.70.132	10.89.14.37	SCTP	98	HEARTBEAT_ACK
664	77.165930401	192.168.70.132	10.89.14.37	SCTP	98	HEARTBEAT
665	77.165940066	10.89.14.37	192.168.70.132	SCTP	98	HEARTBEAT_ACK

Frame 166: 106 bytes on wire (848 bits), 106 bytes captured (848 bits) on interface 0
 Ethernet II, Src: b0:7b:25:23:71:2b (b0:7b:25:23:71:2b), Dst: Dell_6e:5d:27 (8c:ec:4b:6e:5d:27)
 Internet Protocol Version 4, Src: 10.89.14.37, Dst: 192.168.70.132
 Stream Control Transmission Protocol, Src Port: 51122 (51122), Dst Port: 38412 (38412)

Installing, Configuring, and Running the UE System

There are three scenarios for the UE implementation: the USRP radio; the 5G wireless modem module; and the COTS handset.

UE Scenario 1: USRP

The UE can be implemented by running the OAI softmodem with a USRP N300, N310, N320, N321, or X410 device. Currently, this reference architecture is focused on the use of a USRP X410 device, although the integration of the other USRP devices is similar to the integration of the USRP X410 and is relatively straight-forward.

Before installing and configuring the UE system, be sure that you first have configured the system BIOS, implemented the Linux performance tuning settings, and installed UHD.

Building and installing the OAI softmodem software

Note that the procedure for building and configuring the UE software is very similar to the procedure for building and installing the gNB software.

The commands listed below build and install the UE software from source code using the OAI Git repository.

```
git clone https://gitlab.eurecom.fr/oai/openairinterface5g.git
cd openairinterface5g
git checkout 2022.w33
source oaienv
cd cmake_targets
```

Confirm that you are using the correct branch and commit hash. Run the command listed below, and verify that the branch is 2022.w33 and that the commit hash is ad8381a66bb67d6ef7fa94c9a6ae6c66f3ae84b8.

```
git status
```

Edit the build_oai script, and comment out the lines shown below, by adding a hash mark # at the beginning of each line.

```
if [ "$HW" == "OAI_USRP" ]; then
  echo_info "installing packages for USRP support"
  #check_install_usrp_uhd_driver
  #if [ ! "$DISABLE_HARDWARE_DEPENDENCY" == "True" ]; then
  #  install_usrp_uhd_driver $UHD_IMAGES_DIR
  #fi
fi
```

For the very first time that you build the gNB software, use the command listed below, which includes the "-I" option, which installs the package dependencies for the gNB software.

```
./build_oai -I --w USRP
```

For successive builds, use the command listed below, which omits the "-I" option.

```
./build_oai --gNB --w USRP
```

Editing the UE Configuration File

Once we build and install the UE software, we need to modify the UE configuration file. Only one UE configuration file is available in the folder `openairinterface5g/targets/PROJECTS/GENERIC-NR-5G/CONF`. The UE configuration file used in this reference architecture is `ue.conf`. The default contents of the file is shown below.

```
uicc0 = {
  imsi = "2089900007487";
  key = "fec86ba6eb707ed08905757b1bb44b8f";
  opc = "C42449363BBAD02B66D16BC975D77CC1";
  dnn = "oai";
  nssai_sst=1;
  nssai_sd=1;
}
```

Edit the fields `imsi`, `key`, `opc`, `dnn`, `nssai_sst`, `nssai_sd` per the values for the CN. Earlier, when configuring the Docker containers for the CN system, we entered several parameters in the `oai_db1.sql` file. The `imsi`, `key`, `opc` fields there should match the values here in the UE configuration file. The `dnn` value should be same as listed in the `docker-compose-mini-nrf.yaml` file. The `nssai_sst` and `nssai_sd` values should be same as listed in the gNB configuration file and the `docker-compose-mini-nrf.yaml` file.

Invoking the OAI UE softmodem

Run the command listed below to invoke the OAI UE softmodem.

```
openairinterface5g/cmake_targets/ran_build/build sudo ./nr-uesoftmodem --usrp-args "addr=192.168.10.2, clock_source=external,time_source=external" -r 106 --numerology 1 --band 78 -C 3319680000 --sa --nok
```

The command-line option `--usrp-args` specifies the USRP device arguments, which are passed to the UHD driver. Here we specify the IP address of the USRP, along with clocking source and the timing source, which are set to `external`, to indicate the use of the connection to the OctoClock-G device.

The command-line option `-r 106` specifies the PRBS being used. Based on the PRBS, we can calculate the operational channel bandwidth being used (i.e., 40 MHz).

The command-line option `--numerology 1` specifies the SCS being used (i.e., 30 KHz).

The command-line option `--band 78` specifies the 3GPP frequency band being used.

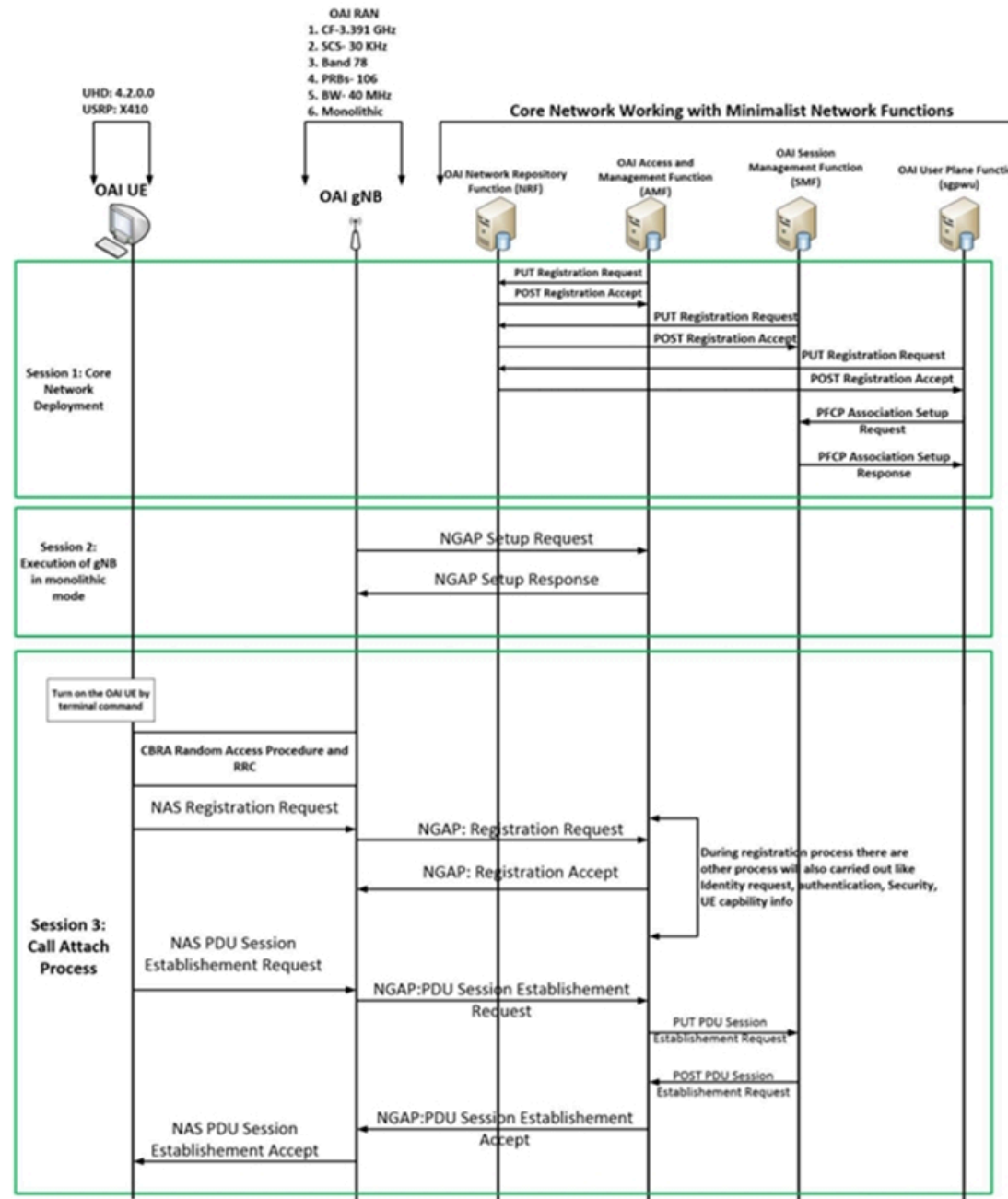
The command-line option `-C 3319680000` specifies the CF we are operating (i.e., 3.319 GHz).

The command-line option `--nokrnmod 1` forces the use of the tunnel interface.

Once the UE is attached to the CN, verify that the `oaitun_ue1` network interface has been created, and that it has been assigned an IP address of 10.x.x.x, using the command listed below.

```
ifconfig
```

The call attach process between the UE and the gNB is illustrated in the sequence diagram shown below.



The relevant lines in the OAI UE softmodem log file show information about the call attach process.

```
[FWT] [SCHED][UE] Check absolute frequency DL 3319480000.000000, UL 3319480000.000000 (RF card 0, oai_exit 0, channel 0, rx_num_channels 1)
[FWT] Starting sync detection
[FWT] [UE thread Synch] Running Initial Synch (mode 4)
[FWT] [UE] rx_synchro_time: Sync source = 0, Peak found at pos 283468, val = 10497327245 (99 dB) avg 43 dB, Efo 0.000000
PSS acquisition duration 250041 microseconds
[FWT] [UE0] Initial sync : Estimated PSS position 283468, Nid2 0
[FWT] sync_pos 283468 sub_offset 283324
[FWT] Calling sss detection (normal CP)
Nid2 0 Nid1 0 tot_metric 41290, phase_max 2
[FWT] [UE0] Initial sync: starting PBCH detection (rx_offset 0)
[NR_NGC] Configuring NAC for first MIB reception
[FWT] [UE0] Initial sync: pbch decoded successfully
[FWT] TDD Normal prefix: CellId 0 metric 41290, phase 2, pbch 0
[FWT] [UE0] In synch, rx_offset 278908 samples
[FWT] [UE 0] SBC Measurements >: rxss -inf dBm (sig -inf dB, gain 110), WU 0 dBm, rxss -inf dBm/RE, rxss -inf dB
[FWT] [UE 0] Measured Carrier Frequency 3319480000 Hz (offset 0 Hz)
[FWT] [UE0] Configuring channel 0 (rf_chain 0): setting tx_freq 3319480000.000000 Hz, rx_freq 3319480000.000000 Hz
[FWT] Got synch: bw_slot_offset 18, carrier_off 0 Hz, rxgain 110.000000 (DL 3319480000.000000 Hz, UL 3319480000.000000 Hz)
Setting USRP TX Freq 3319480000.000000, RX Freq 3319480000.000000
[NR_NGC] SIB1 decoded
[NR_NGC] NR band duplex spacing is 0 KHz (nr_bbandtable[37].band = 78)
[NR_NGC] NR band 78, duplex mode TDD, duplex spacing = 0 KHz
[NR_NGC] Setting TDD configuration period to 4
[FWT] TDD has been properly configured
[NR_NGC] Initializing ul_config request - num_slots_ul = 3
[NR_NGC] [UE 0] : Logical Channel UL-CCCH (SRB0), Generating RRCSetupRequest (bytes 4, gNB 0)
[FWT] Resynchronizing RX by 278908 samples (mode = 4)
[FWT] !!!adjusting +1 samples!!! rx_offset == -4
[NR_NGC] Initialization of 4-step contention-based random access procedure
[FWT] PRACH [UE 0] in slot 19, placing PRACH in position 2028, mag1 frequency start 0 (kl 0), preamble_offset 0, first_honzero_root_LMA 0
[NR_NGC] [UE 0][RAPPROC] Got SI RAR subPDU 3 ms
[NR_NGC] [UE 0][RAPPROC] Got RAPID RAR subPDU
[NR_NGC] [UE 0][RAPPROC][208.7] Found RAR with the intended RAPID 0
[NR_NGC] [RAPPROC][208.17] RA-Msg0 transmitted
[FWT] !!!adjusting +1 samples!!! rx_offset == -4
[NR_NGC] [UE 0][RAPPROC] Frame 210 : received contention resolution identity: 0a1ab77c0b3f84 Terminating RA procedure
[NR_NGC] [UE 0][210.1][RAPPROC] RA procedure succeeded. CB-RA: Contention Resolution is successful.
```

Launch Wireshark to view the packets exchanged between the UE and gNB for this call attach process.

91 7.610958913	10.89.14.37	192.168.70.132	NGAP	126 NGSSetupRequest
93 7.612847252	192.168.70.132	10.89.14.37	NGAP	574 NGSSetupResponse
464 36.256949373	10.89.14.37	192.168.70.132	NGAP	126 NGSSetupRequest
466 36.258622435	192.168.70.132	10.89.14.37	NGAP	574 NGSSetupResponse
846 89.060510902	10.89.14.37	192.168.70.132	NGAP/NAS-SGS	146 InitialUEMessage, Registration request
847 89.068282411	192.168.70.132	10.89.14.37	NGAP/NAS-SGS	630 DownlinkNASTransport, Authentication request
848 89.219989741	10.89.14.37	192.168.70.132	NGAP/NAS-SGS	146 UplinkNASTransport, Authentication response
849 89.221168848	192.168.70.132	10.89.14.37	NGAP/NAS-SGS	462 DownlinkNASTransport, Security mode command
850 89.300181978	10.89.14.37	192.168.70.132	NGAP/NAS-SGS/NAS-SGS	174 UplinkNASTransport, Security mode complete, Registration request
851 89.302116707	192.168.70.132	10.89.14.37	NGAP/NAS-SGS	1390 InitialContextSetupRequest, Registration accept
852 89.370549572	10.89.14.37	192.168.70.132	NGAP	122 UERadioCapabilityInfoIndication
855 89.574529982	10.89.14.37	192.168.70.132	NGAP	86 InitialContextSetupResponse
861 90.400109630	10.89.14.37	192.168.70.132	NGAP/NAS-SGS	118 UplinkNASTransport, Registration complete
864 90.602530712	10.89.14.37	192.168.70.132	NGAP/NAS-SGS	146 UplinkNASTransport, UL NAS transport, PDU session establishment request
865 90.607182312	192.168.70.132	10.89.14.37	NGAP/NAS-SGS	266 PDUSessionResourceSetupRequest, DL NAS transport, PDU session establishment accept
866 90.700380878	10.89.14.37	192.168.70.132	NGAP	122 PDUSessionResourceSetupResponse

Verify that the UE was connected to the gNB

To verify that UE has successfully attached to the gNB, check the OAI-AMF logs on the CN machine using the command listed below. Check the output to confirm that UE has been registered by the Core Network.

```
sudo docker logs oai-amf
```

Run `ifconfig` on the UE machine to check the IP address assigned to the UE. Verify that the `oaitun_ue1` network interface has been created, and that it has been assigned an IP address of 10.x.x.x. You can also check the OAI-SMF logs using the command listed below.

```
sudo docker logs oai-smf
```


UE Scenario 2: 5G Wireless Modem Module

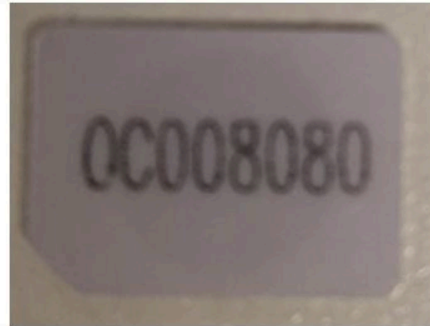
The UE can be implemented using a 5G wireless modem module. Currently, this reference architecture is focused on the use of a Quectel RM500Q-GL 5G wireless modem module. This device is a 5G NR sub-6GHz M.2 module which meets the 3GPP Release 15 specification, and is optimized for industrial and commercial IoT and eMBB applications. It supports both standalone (SA) and non-standalone (NSA) modes. Other wireless modem modules can certainly be used as well. Detailed documentation for the Sierra Wireless EM9191 module will be added in the near future.

Configuring the SIM Card

When using a 5G wireless modem module or a COTS handset, a SIM card will be required. If a USRP is being used as the UE, running the OAI UE softmodem, then a SIM card is not required.

The SIM card used in this reference architecture is provided by Open-Cells, and is shown below. Note that the ADM code is printed directly on the SIM card itself.





Insert the nano SIM card into the SIM card reader/writer, and plug it into the USB slot on the UE computer.

To read and program the SIM card, we use the program `program_uicc` from Open-Cells (here).

We first read the existing data on the SIM by running the command below.

```
sudo ./program_uicc --adm 1
```

```
gnb@gnb-Precision-5820-Tower-X-Series:~/Downloads/uicc-v2.4$ sudo ./program_uicc --adm 1
Existing values in USIM
ICCID: 89860061100000000101
WARNING: iccid luhn encoding of last digit not done
USIM IMSI: 208920100001101
USIM MSISDN: 00000101
USIM Service Provider Name: OpenCells101
No ADM code of 8 figures, can't program the UICC
gnb@gnb-Precision-5820-Tower-X-Series:~/Downloads/uicc-v2.4$
```

We then write the key and the OPC in the UICC file in the SIM card. The ADM value enables this. Run the command below to perform this operation, where ADM_VALUE_FROM_SIM is the ADM value printed directly on the SIM card itself.

```
sudo ./program_uicc --adm <ADM_VALUE_FROM_SIM> --key 0C0A34601D4F07677303652C0462535B --opc 63bfa50ee6523365ff14c1f45f88737d --authenticate --noreadafter
```

```
mb@gnb-Precision-S820-Tower-X-Series: ~$ sudo ./program_uicc --adm 0C000000 --key 0C0A34601D4F07677303652C0462535B --opc 63bfa50ee6523365ff14c1f45f88737d --authenticate
Existing values in USIM
ICCID: 8986006110000000101
WARNING: iccid luhn encoding of last digit not done
USIM IMSI: 208920100001101
USIM MSISDN: 00000101
USIM Service Provider Name: OpenCells101
Setting new values
Reading UICC values after uploading new values
ICCID: 8986006110000000101
WARNING: iccid luhn encoding of last digit not done
USIM IMSI: 208920100001101
USIM MSISDN: 00000101
USIM Service Provider Name: open cells
Succeeded to authenticate with SQN: 64
set HSS SQN value as: 96
mb@gnb-Precision-S820-Tower-X-Series: ~$ sudo ./program_uicc --adm 1
```

Ensure that the values being programmed into the SIM card match the corresponding values entered in the SQL database on the CN machine. The values of primary importance are listed in the table below.

Primary Configuration Parameters for UE, gNB, CN

Parameter	UE	gNB	CN
IMSI	208920100001101	MCC: 208, MNC: 92	208920100001101
MSISDN	00000101		00000101
IMEI	863305040549338		863305040549338
Key	0C0A34601D4F07677303652C0462535B		0C0A34601D4F07677303652C0462535B
OPC	63bfa50ee6523365ff14c1f45f88737d		63bfa50ee6523365ff14c1f45f88737d

Serial Connection to the Module via Minicom

Attach all four antennas to the Quectel wireless modem module. Then, mount the Quectel module into the M.2 connector slot on the carrier board. Then, connect the carrier board to the UE computer via a USB 3.0 port.

We will use Minicom to communicate with the Quectel module over a USB serial connection. Run `which minicom` to verify that Minicom is already installed. If not, then run the command listed below to install it.

```
sudo apt-get install minicom
```

Once the Quectel module is plugged in, the Linux operating system should create several USB serial devices which can be used to communicate with the module. The default device should be `/dev/ttyUSB0`. Run the command listed below to start a Minicom serial console session with the Quectel device.

```
sudo minicom /dev/ttyUSB0
```

Note that in order to exit Minicom, type Ctrl-A, then "X".

AT Commands for the Module

We use Minicom to issue AT Commands to the 5G modem module.

There are informative articles about AT Commands [here](#) and [here](#).

There are some specific AT Commands that we need to control and query the Quectel module. The AT Command are generally not case-sensitive. Execute all the AT Commands listed below, in-order, to setup and configure the Quectel module.

AT+GMR

Display the current firmware version number.

AT+CIMI

Display the IMSI of the (U)SIM.

AT+GSN

Display the IMEI of the (U)SIM.

```
AT+QMBNCFG="select","ROW_Commercial"
```

Unlock the Quectel module.

```
AT+qnwprefcfg="nr5g_band"
```

Display which 5G NR frequency bands are configured.

```
AT+qnwprefcfg="mode_pref"
```

Display which 5G NR mode is set.

```
AT+qnwprefcfg="mode_pref",nr5g
```

Set the operational mode to 5G NR SA.

```
AT+qnwprefcfg="nr5g_disable_mode",0
```

Enable 5G NR operations.

```
AT+cgdcont=1,"IP","oai","0.0.0.0",0,0 (cid, pdp type, apn, pdp_addr, data_comp, head-comp)
```

Specify the PDP context parameters for a specific context cid.

AT+CFUN=0

Set the minimum functionality of the module.

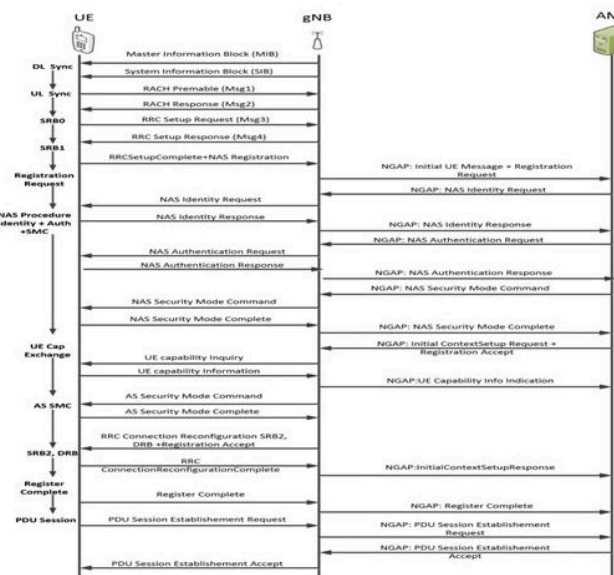
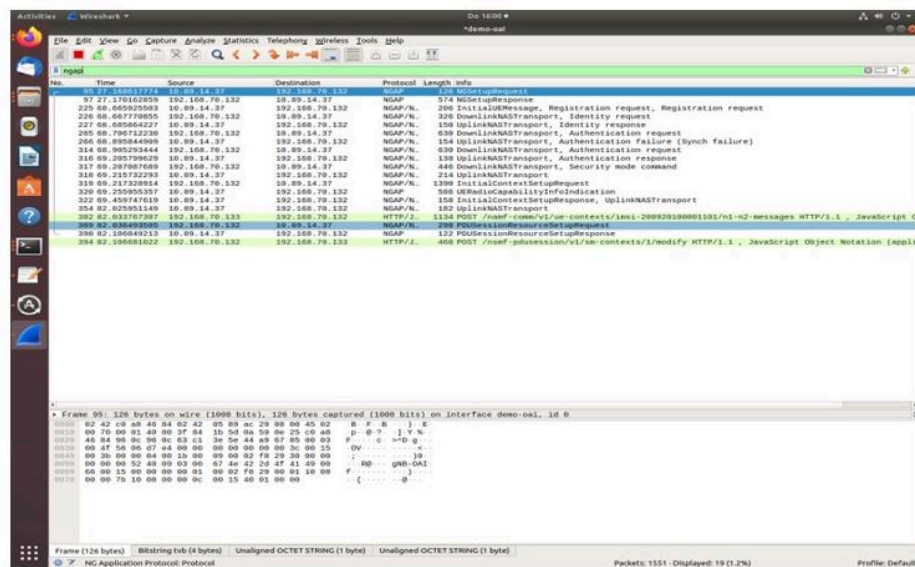
AT+CFUN=1

Set the full functionality of the module.

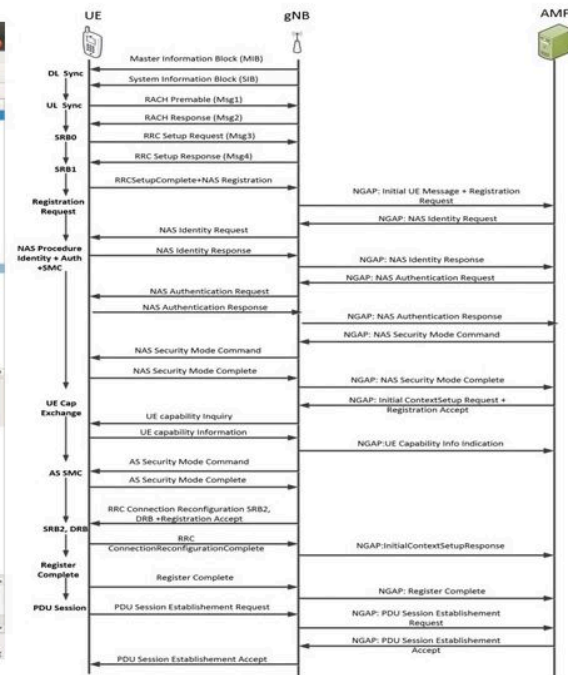
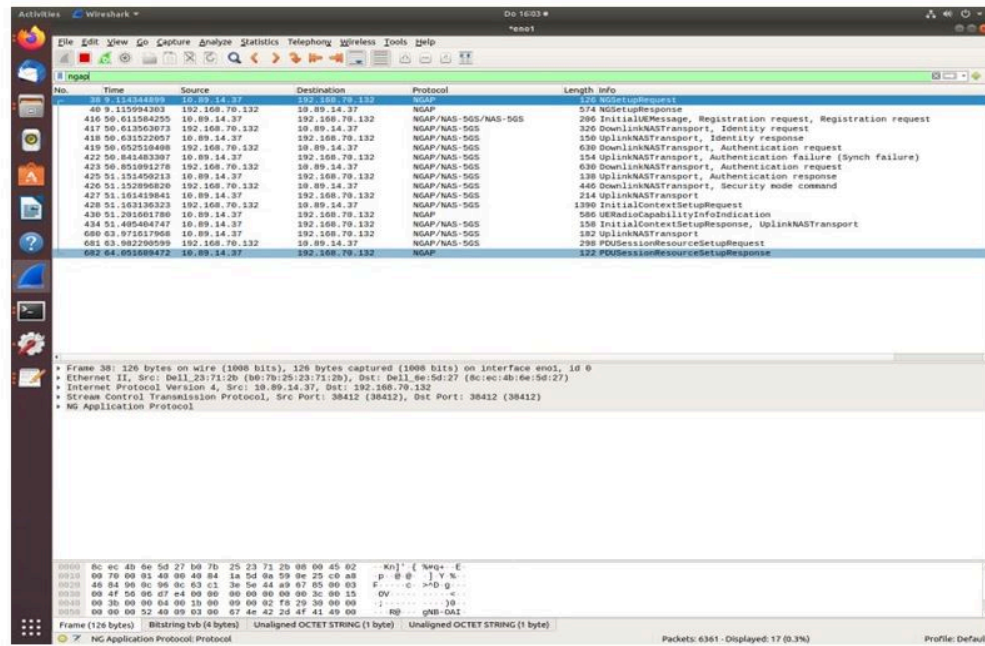
Verifying the Operation with Wireshark

Once all the AT Commands have been executed, we should see msg1, msg2, msg3, msg4, RRC logs on the gNB and the registration request from the UE to the AMF on Wireshark.

The screenshot below shows Wireshark running on the CN machine, and shown on the right is the corresponding sequence diagram showing the message exchanges between the UE, gNB, and CN AMF, from the perspective of the CN machine.



The screenshot below shows Wireshark running on the gNB machine, and shown on the right is the corresponding sequence diagram showing the message exchanges between the UE, gNB, and CN AMF, from the perspective of the gNB machine.



Verifying the Operation with AT Commands

We run the AT Commands listed below in Minicom, and examine the responses, to verify the operation of the system.

AT+COPS?

This output specifies the current operators and their status.

Expected Output: 0,0,"208 92 open cells",11

Field 1: Availability of Operators, where 0 specifies Unknown

Field 2: Operator Selection of operators, where 0 specifies Automatic

Field 3: Operator Name, where 208 92 Open cell specifies pre-programmed operator name

Field 4: Access Technology Selected, where 11 specifies 5G NR connected to a 5G CN

AT+C5GREG?

The output of this command shows the 5G network registration status.

Expected Output: 2,1,"1", "0", 11, 16, "01.00007B;00.000000;01.00000C;00.000000"

Field 1: Enable network registration and location information, where 2 specifies Unsolicited Mode

Field 2: Registration Status, where 1 specifies Registered on Home Network

Field 3: 1 specifies a three-byte tracking area code in hexadecimal format

Field 4: 0 specifies a five-byte (NR) cell ID in hexadecimal format

Field 5: 11 specifies that the connection mode is 5G NR connected to a 5G CN

Field 6: 16 specifies the number of octets of the allowed NSSAI information element

Field 7: 01.00007B;00.000000;01.00000C;00.000000 specifies the allowed NSSAI

UE Scenario 3: COTS Handset

The UE can be implemented using the commercial (COTS) handset. This reference architecture will feature the use of the Google Pixel 5A handset. Detailed documentation about this will be added in the near future.

End-to-End Verification

Using ping

We run `ping` on the CN machine to verify connectivity from the CN, through the gNB, to the UE. Run the command listed below on the CN machine. Replace 12.1.1.x with the correct IP address of the UE, as assigned by the CN.

```
sudo docker exec -it oai-ext-dn ping 12.1.1.x
```

Using iperf

We use `iperf` to measure the throughput in bits per second for the Downlink (DL) and for the Uplink (UL).

Downlink

For the Downlink, the client runs on the CN machine, and the server runs on the UE machine.

Run the command listed below on the client. Replace 12.1.1.x with the correct IP address of the UE, as assigned by the CN.

```
sudo docker exec -it oai-ext-dn iperf -c 12.1.1.x -u -b yM --bind 192.168.70.135
```

Run the command listed below on the server. Replace 12.1.1.x with the correct IP address of the UE, as assigned by the CN.

```
iperf -s -i 1 -u -B 12.1.1.x
```

Uplink

For the Uplink, the client runs on the UE machine, and the server runs on the CN machine.

Run the command listed below on the client. Replace 12.1.1.x with the correct IP address of the UE, as assigned by the CN.

```
iperf -c 192.168.70.135 -u -b yM --bind 12.1.1.x
```

Run the command listed below on the server. Replace 12.1.1.x with the correct IP address of the UE, as assigned by the CN.

```
sudo docker exec -it oai-ext-dn iperf -s -i 1 -u -B 192.168.70.135
```

Technical Support

The primary method of technical support is through mailing lists and direct email.

USRP Mailing List

The usrp-users mailing list is for discussions specifically involving the USRP hardware and the UHD software.

<https://lists.ettus.com/list/usrp-users.lists.ettus.com>

The list archives can be found at the link below.

<https://lists.ettus.com/empathy/list/usrp-users.lists.ettus.com>

OAI Mailing List

There are two mailing lists, openair5g-user and openair5g-nr, which are for discussions specifically involving the Open Air Interface (OAI) software stack. More information can be found at the links below.

<https://gitlab.eurecom.fr/oai/openairinterface5g/-/wikis/MailingList>

<https://gitlab.eurecom.fr/oai/openairinterface5g/-/wikis/AskQuestions>

Email

You can contact the authors about the reference architecture directly via email at support@ettus.com.

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