Open RAN Direct RF Sampling Radio Transceiver Architectures for Massive MIMO

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Abstract

With the exponential increase in wireless traffic, mobile networks are transformed into more software-driven, virtualized, flexible, intelligent, and energy efficient systems. These trends have stimulated significant change in the core network with the advent of software defined networks (SDN) and network functions virtualization (NFV), which have enabled building more agile and less expensive network entities. However, the radio access network (RAN) largely remained unchanged until recently, despite the fact that the majority of the capital expenditures (CAPEX) and operating expenses (OPEX) in building and managing of networks resulted from the RAN deployment. Traditionally, RAN components such as radio transceivers and baseband were implemented on proprietary hardware and these components typically used vendor-specific protocols for communications. The software and interfaces between different RAN components were customized for optimal performance of the proprietary hardware. Disaggregated base station architecture with open interfaces was introduced in 5G to allow multi-vendor solutions while ensuring interoperability of various components. A key challenge arising from the migration toward open-RAN architectures is the scale and flexibility of deployment, optimization, security, management, and orchestration of the network.

RAN cloudification was one of the fundamental tenets of the open-RAN architecture. Cloud-RAN architecture addressed capacity, flexibility and coverage issues, while supporting mobile fronthaul and/or backhaul solutions as well as network self-organization, self-optimization, configuration, and adaptation with software control and management through SDN and NFV techniques. Cloud-RAN has also provided advantages in managing operational costs, improving network security, network controllability, network agility, and flexibility. Considering the migration of the networks toward virtualization and SDN control, the use of programmable and fully configurable cloud-RAN components is essential, to minimize operators' CAPEX and OPEX when deploying networks in different scenarios and geographies.

Massive multiple-input, multiple-output (MIMO), as one of the key enablers of 5G new radio, requires scalable, adaptable, optimized partitioning and integration of complex digital and RF signal processing functions. Meeting the challenges of 5G wireless access involves significant changes to existing radio architectures. New architectures will leverage the latest innovations to better utilize existing spectrum and improve the capacity of networks using techniques like carrier aggregation and beamforming to implement adaptive active arrays. The cost associated with moving data between these new RF frontends and the digital frontend is one of the major issues that must be resolved to make these new technologies commercially viable. Another key requirement is increased adaptability and programmability of the RF frontend to reduce time to market and to provide a platform that addresses the wide range of emerging radio requirements [REF 1]. A new generation of semiconductor technology which combines programmable logic with integrated radio frequency data converters would allow design of radio units based on direct RF sampling radio transceiver architecture. See also *An Adaptable Direct RF-Sampling Solution* (WP489).

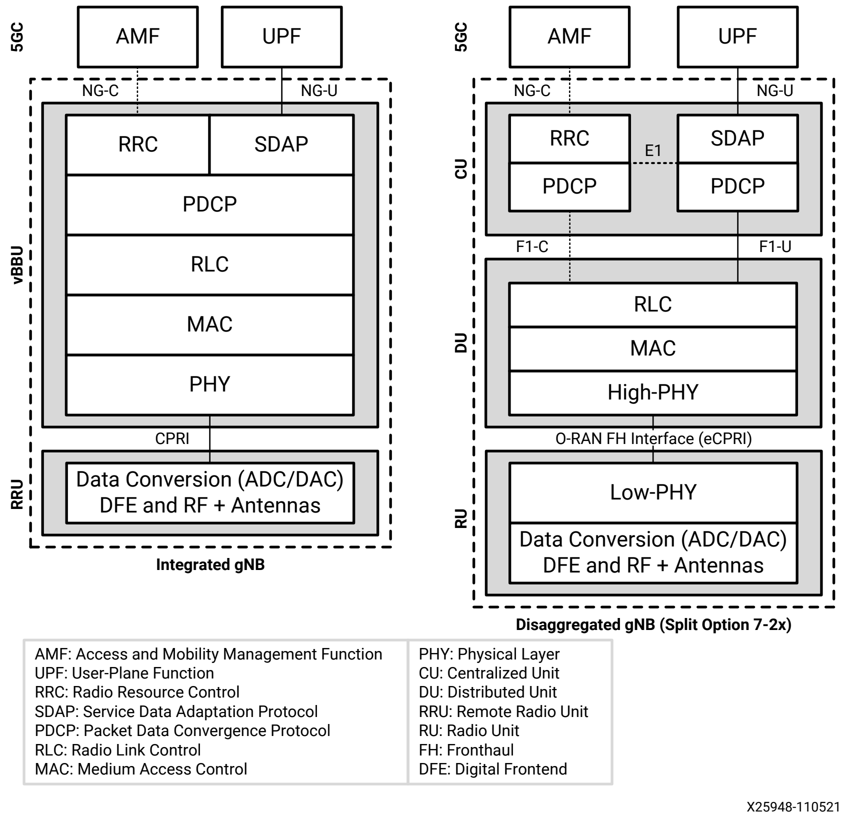
This white paper describes a scalable, modular, programmable, and SDN-configurable radio unit reference design, which can provide various connectivity options toward the baseband unit including the open fronthaul interface specified by the Open RAN Alliance, support flexible functional splits, and deliver a platform for supporting massive MIMO operation using an integrated or discrete array of active antennas.

Introduction and Background

The traditional RAN comprised monolithic base stations with integrated functions. It had multiple components including a baseband processing unit, cables and connectors, the RF processing unit, and the antenna subsystem, provided as a single RAN package by the major OEMs. A disaggregated RAN architecture splits the base station into three distinct parts: a centralized unit (CU), a distributed unit (DU), and a radio unit (RU). Combined with the notion of open interfaces, this would create a new realm of possibilities, allowing operators to choose different hardware based on the needs of a particular node. The CU and the DU can be provided by different vendors, and operators can choose the amount of processing power and additional functionalities that they require based on their deployment scenario. In traditional RAN architectures, the hardware was specialized using x86 or Arm®-based processors, and customized for a handful of RAN vendors, whereas the Open RAN stack can run on general-purpose white-box hardware with the software functionality effectively decoupled from the underlying hardware. While this separation is taken for granted in enterprise data centers, it is just gaining traction in mobile networks.

In a cloud-RAN architecture, a 5G base station (gNB) can be functionally disaggregated such that some lower-layer protocol functions are implemented in the distributed units and the remaining upper layer protocol functions are implemented in the edge cloud and as part of the centralized unit to alleviate the capacity limits of the fronthaul links, as depicted in the following figure. Based on the distributed base station architecture model for cloud-RAN, some of the upper-layer functions are performed in the centralized unit, whereas lower-layer L1 functions are typically split between the distributed unit and a number of radio units. The CU and DU are collectively referred to as baseband unit (BBU). In such architectures, the RUs are connected to a BBU pool through high-bandwidth transport link known as fronthaul.

Figure 1: **Comparison of Integrated and Disaggregated Base Station Architectures**



One of the main differentiators and benefits of 5G network architectures compared to legacy generations is the decomposition of the RAN into functional components, which include radio units, distributed units and centralized units with the corresponding connectivity segments of fronthaul (RU to DU), mid-haul (DU to CU) and backhaul (CU to the core network). One benefit is the greater flexibility that drives greater coordination and efficiencies in the RAN. Another benefit is the prospect of an open RAN comprising functional components supplied by different radio vendors.

There are a few standard transport options between the RU and the BBU including common public radio interface (CPRI), radio-over-Ethernet (RoE), and Ethernet which primarily use optical links. However, CPRI and its most recent version, eCPRI, are currently the most common transport protocols used by cloud-RAN equipment vendors [REF 2][REF 3].

The encapsulation and mapping of radio protocols for transport over Ethernet frames, using radio over Ethernet (RoE), are defined in IEEE 1914.3-2018. Structure-agnostic definitions are provided for any digitized radio data. Structure-aware definitions are provided for CPRI. Native mode definitions are provided for digitized radio in-phase and quadrature (I/Q) payload.

The main advantage of an Open RAN architecture is understood by how it unbundles traditionally end-to-end solutions from a handful of major vendors and offers more selectivity to operators in their respective network deployments when procuring network equipment. The uncoupling of hardware and software and priority toward virtualized network functions can ideally help operators reduce both capital and operational expenditures (CAPEX and OPEX). This can be achieved by eliminating vendor dependencies and providing supplier diversity, thereby expanding the ecosystem while leveraging Open RAN's embedded network intelligence layers to enable automation and self-optimization. A crucial aspect in designing a fully modularized virtual network running on commercial off-the-shelf (COTS) servers is establishing Open RAN-compliant interface protocols. The traditional fronthaul interface, CPRI, facilitated data communication between the remote radio units and the baseband unit. The main problem with CPRI is its vendor-specific and proprietary implementation. The network operators would therefore have to rely on a single vendor when procuring more BBU/RUs in their network due to the existence of an inflexible and somewhat proprietary interface. The introduction of the Open RAN-compliant interface Enhanced CPRI (eCPRI) transport mechanism paved the way for the operators to have more options in complementing their RU/BBU equipment from different vendors.

The X_2/X_n is another network interface that is dominated by proprietary technology that bridges communication between different eNBs/gNBs (LTE/NR base stations) in mobile networks [REF 4]. The 3GPP-defined X2-AP/Xn-AP protocol allows the X_2/X_n interface to support information exchange between eNBs/gNBs for the purpose of user data forwarding, traffic/load management, interference coordination, and inter-eNB/gNB messaging. The opening of this interface is especially critical for non-standalone (NSA) 5G architectures that rely on the coexistence between 4G and 5G base stations. A vendor specific X_2/X_n interface restricts operators' NSA 5G network development only to their existing 4G vendors. The Open RAN X_2/X_n specifications solve this problem by establishing interoperability between 4G eNBs and 5G gNBs provided by multiple vendors in NSA 5G network deployments.

The Small Cell Forum has also contributed to the Open RAN efforts by extending the functional application platform interface (FAPI) and network FAPI (nFAPI) interfaces of small cells to 5G disaggregated base stations. The FAPI uses a common set of APIs for the interoperability of the hardware, software, and applications in small cells. The nFAPI, on the other hand, is more pertinent to virtualized 5G network entities because it defines an open interface between the virtualized DU and CU.

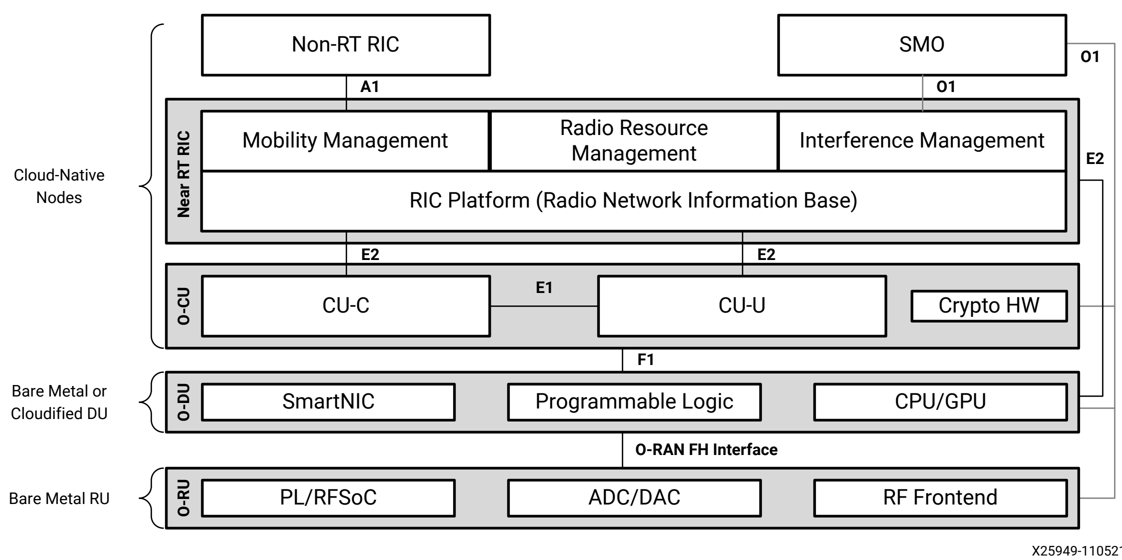
One of the key technology areas that deserves more attention in the push to develop competitive open radio access network solutions is diverse supply of radio units. This, in turn, requires a better supply of the RF modules used to build power-efficient, cost-competitive RUs. Competitive, open RAN RU products are important because the transmit RF chain; i.e., CPRI interfaces, digital-to-analog converters, power amplifiers, filters, antenna subsystems, typically accounts for about 70% of the bill-of-material of a cellular base station. Considering that the RU consumes most of the power and a major part of the real estate needed to deploy a base station, it also accounts for a significant portion of the operating cost. Incumbent vendors with large product volumes and long-standing relationships with silicon suppliers can afford the expertise, time and financial cost to design and construct these solutions. However, for many in the broader ecosystem, from new entrants to mid-sized RAN players, radio hardware is an expensive and difficult proposition.

O-RAN System Requirements and Deployment Scenarios

The Open RAN Alliance (O-RAN) was founded in 2018 by a group of leading operators and has been organized in various working groups, each focusing on a specific area, specifying the required elements of the disaggregated base station model, which includes hardware and software architectures of CU, DU, and RU and the open interfaces as well as cloudification and orchestration mechanisms for management and control of the virtualized functions. As shown in the following figure, O-RAN defines the RAN architecture with a focus on new, open interfaces between the logical nodes and physical partitions of the RAN functions. In some RAN deployment scenarios; e.g., a pico-cell or macro-cell, the physical layer is split between the DU and RU. O-RAN working group 4 has defined an open fronthaul interface which was adopted in the split architecture described in the next section. The DU contains the higher physical layer functions, while the RU hosts the lower physical layer functions as specified in [REF 5] [REF 6]. O-RAN working group 7 is chartered with defining hardware architecture requirements and reference designs for the O-RAN compliant CU, DU and RU which are henceforth referred to as O-CU, O-DU, and O-RU.

A high-level view of the O-RAN architecture is illustrated in the following figure. It shows that four key interfaces namely, A1, O1, open fronthaul M-plane, and O2, connect service management and orchestration (SMO) framework to O-RAN network functions and the O-Cloud. O-Cloud is a cloud computing platform comprising a collection of physical infrastructure nodes that meet O-RAN requirements to host the relevant O-RAN functions (such as near-RT RIC, O-CU-CP, O-CU-UP, and O-DU), the supporting software components (such as operating system, virtual machine monitor, container run time, etc.) and the appropriate management and orchestration functions [REF 5].

Figure 2: **O-RAN Architecture and Interfaces**



The figure further illustrates how the O-RAN network functions can be virtualized network functions (VNFs); i.e., VMs or containers, sitting above the O-Cloud and/or physical network functions (PNFs) utilizing customized hardware. All O-RAN network functions are expected to support the O1 interface when interfacing the SMO framework [REF 5].

The open fronthaul M-plane interface, between SMO and O-RU, is meant to support the O-RU management in a hybrid model, as specified in [REF 7]. It is an optional interface to the SMO that is included for backward compatibility purposes. Within the logical architecture of O-RAN, as shown in the previous figure, the radio-network side includes near-real-time RAN intelligent controller (RIC), O-CU-CP, O-CU-UP, O-DU, and O-RU functions.

An O-RAN near-RT RAN intelligent controller is a logical function that enables near-real-time control and optimization of RAN elements and resources via fine-grained data collection and actions over E2 interface. It can include AI/ML workflow including model training, inference and updates.

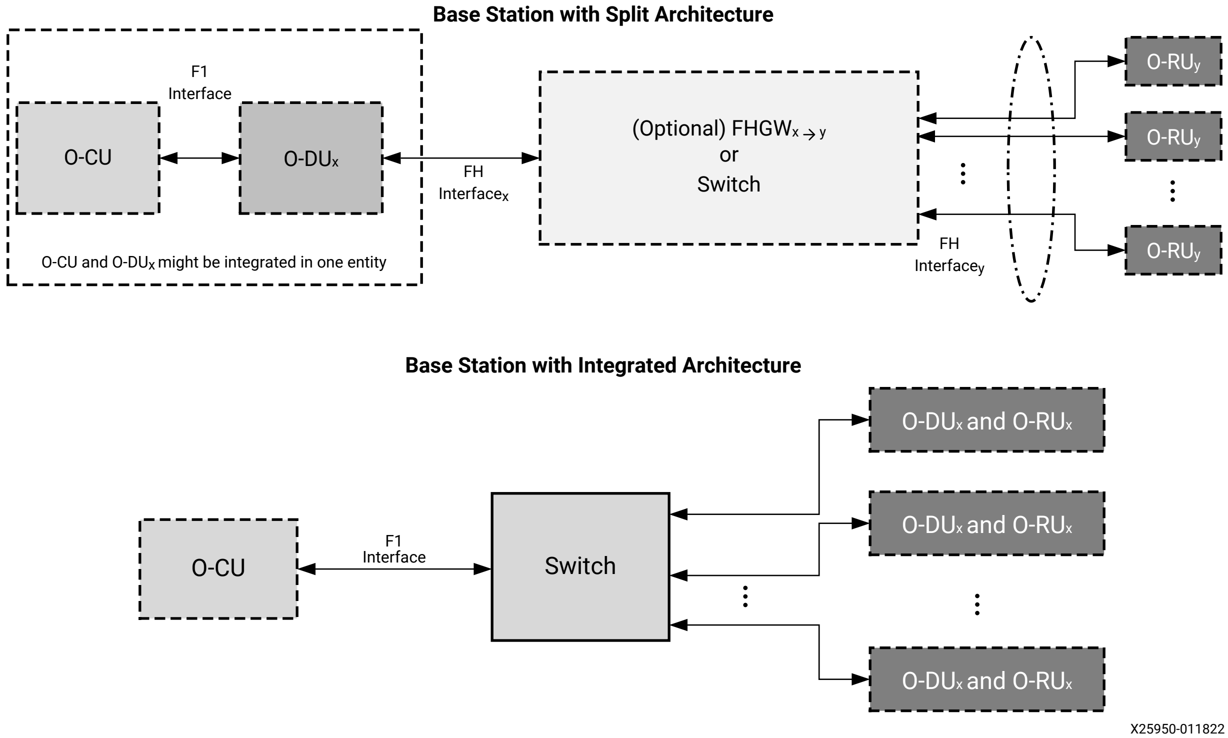
The E2 interface connects the O-eNB to near-RT RIC. Although not shown in this figure, the O-eNB supports O-DU and O-RU functions with an open fronthaul interface between them. As stated earlier, the management side includes SMO framework containing a non-RT RIC function. An O-RAN non-real-time RAN intelligent controller is a logical function within SMO that enables non-real-time control and optimization of RAN elements and resources, AI/ML workflow including model training, inference and updates, and policy-based guidance of applications/ features in near-RT RIC. The O-RU terminates the open fronthaul M-plane interface towards the O-DU and SMO [REF 5].

Disaggregated Base Station Architectures

For any deployment scenario, the 5G base station architectures fall into two categories; i.e., a split or an integrated architecture. The split architecture is illustrated in the following figure where O-CU and O-DU are connected via a switch or a fronthaul gateway (FHGW) to multiple O-RUs. The O-CU is located at the data center and O-DU can be placed either at the data center or at the cell site. Depending on how much intelligence one requires to implement in O-RU or O-DU, there will be a functional split that divides functions of physical layer between O-DU and O-RU. The O-CU and O-DU may be implemented as an integrated entity in one hardware box or as two separate boxes. For downlink, FHGW distributes data to all O-RUs. For uplink, it aggregates the uplink data from all subtending O-RUs according to the cell layout. An open fronthaul interface that meets the O-RAN criteria is also defined.

The following figure illustrates O-RAN integrated and split base station architectures, where the dashed lines are representative of white boxes. In some cases, the figures use specific terminologies (e.g., O-DU$_x$ and O-RU$_x$) to demonstrate compliance to a specific split option. The FHGW$_{x \rightarrow y}$converts split option x from an O-DU$_x$ to split option y toward an O-RU$_y$. The fronthaul multiplexer (FHM) distributes/aggregates data to/from several O-RUs supporting the same split option [REF 7].

Figure 3: **O-RAN Split and Integrated Base Station Architectures**



Given that in a split architecture, O-DU$_x$ and O-RU$_x$ are physically separated by fronthaul interface, depending on the split option, certain functions of base stations may either be performed in O-DU$_x$ or O-RU$_x$. There are eight different fronthaul split options specified by third generation partnership project (3GPP); however, O-RAN only considers the following split options [REF 6]:

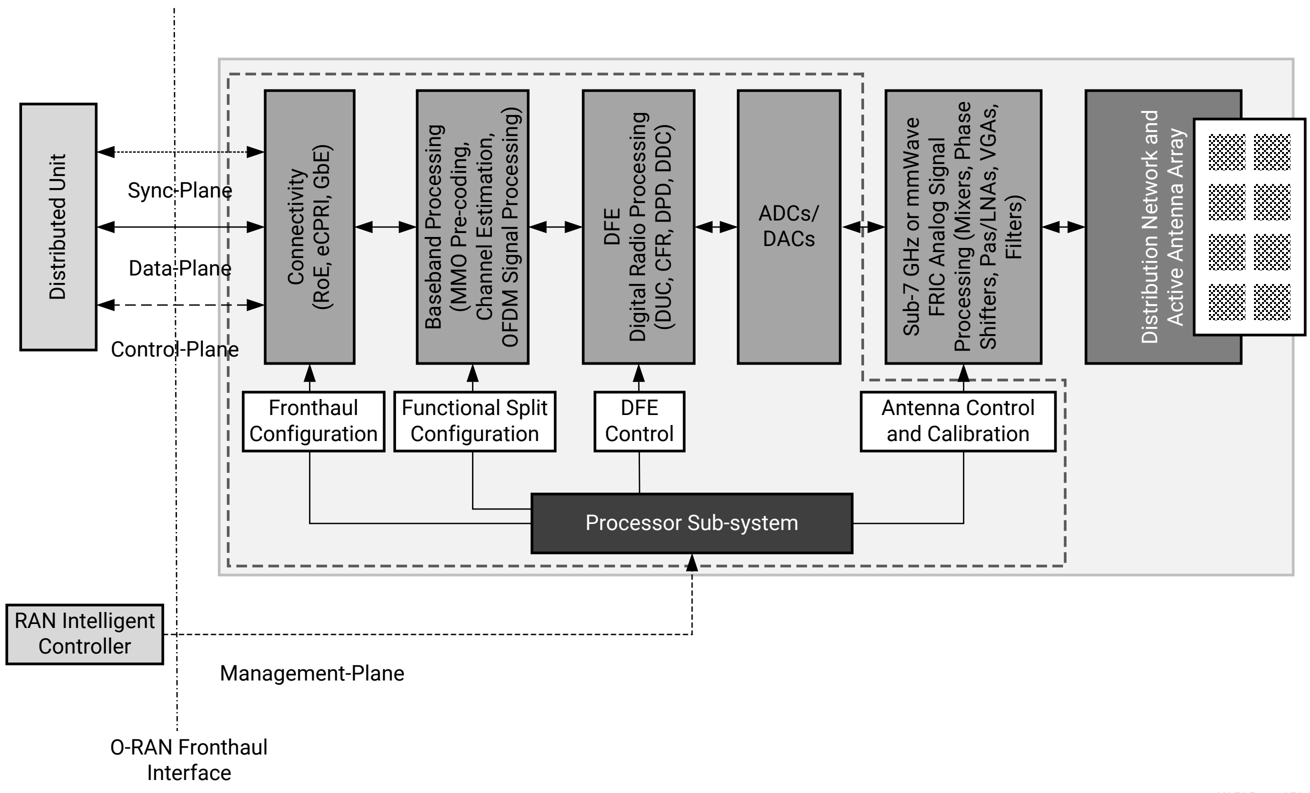
- **Split Option 6:** All physical layer functions reside in O-RU$_x$ while MAC functions are performed in O-DU$_x$. In other words, only uncoded user data traverses the fronthaul. This split is used for the nFAPI interface that is defined by the small cell forum (SCF).
- **Split Option 7-2:** The physical layer (PHY) is split into high-PHY and low-PHY functions, where high-PHY functions; i.e., channel coding, rate matching, scrambling, modulation, and layer mapping, are performed in O-DU$_x$ while O-RU$_x$ performs the low-PHY functions; i.e., precoding, resource mapping, digital beamforming, IFFT, and CP insertion. The I/Q samples are in frequency domain.
- **Split Option 8:** All physical layer functions are performed in O-DU$_x$. This means that the functionality of O-RU$_x$ is limited to digital front-end (DFE) functions, which include digital up-conversion (DUC), crest factor reduction (CFR), and digital pre-distortion (DPD) in the downlink, and digital down-conversion (DDC) in the uplink. The O-RU$_x$ further includes data conversion (ADC/DAC), and analog RF processing functions (timing circuitry, TX/RX filtering, PA, LNA, frequency up/down conversion, and antenna module). The I/Q samples over the fronthaul interface are represented in the time-domain.

An integrated architecture is defined where O-DU$_x$ and O-RU$_x$ are physically co-located in one hardware box and as such no fronthaul interface is required to connect them. The previous figure illustrates the base station with an integrated architecture. For the integrated architecture, an open F1 interface is used between O-CU and O-DU$_x$.

O-RAN Fronthaul and Radio Unit

The high-level architecture of an example radio unit is shown in the following figure. The hardware platform comprises programmable logic, processor sub-system, integrated high-speed ADC/DACs for data conversion, synchronization timing circuitry, and analog RF circuitry (i.e., filters, VGAs, LNAs, combiners/dividers, PAs, synthesizers, and the antenna sub-system). The antenna module contains physical antennae, RF signal distribution/aggregation network, phase shifters, and calibration network. Depending on the choice of functional split, the digital frontend, connectivity, beamforming, and OFDM modulation as well as antenna array control software (for beam steering and beam switching) can be implemented on the programmable logic and embedded processor. The integrated high-speed data converters allow direct RF conversion in sub-7 GHz frequency bands and direct IF processing using a single-stage mixer for the mmWave spectrum. Active antenna arrays are used as the radiating elements.

Figure 4: **High-Level Architecture of the Radio Unit**

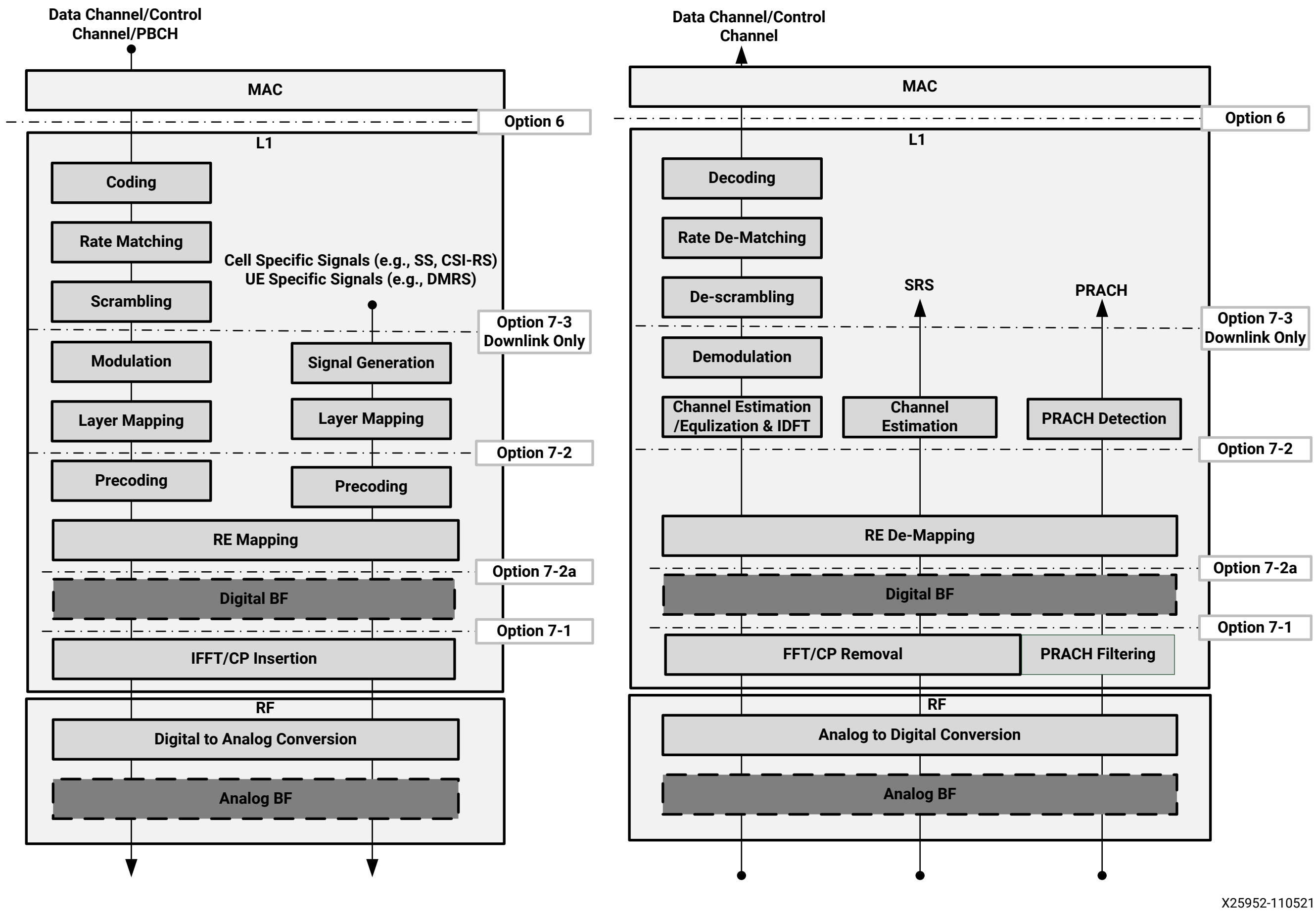


The O-RU implementation is based on open/standard, programmable interfaces which can immensely impact operators' plans for 5G deployments in various scenarios. The gradual migration of systems from 4G to 5G would be an attractive use case for the proposed radio unit architecture, which can reduce the cost of network upgrades and expansion. SDN-controllability; i.e., remote configuration and control by network orchestration and management entity, and dynamic hardware programmability and ease of upgrades are key features of the featured architecture, which is primarily focused on making 5G networks more ubiquitous and adaptable to user applications in various regions.

In O-RAN, open fronthaul interface is defined as the one-to-one or one-to-many link(s) between the O-DU and the O-RU(s). The previous generations of cellular systems used CPRI as the interface between the BBU and the remote radio units. While simple in design, CPRI required significant transport bandwidth proportional to the bandwidth of the baseband signal and the number of antennas. This disadvantage poses a significant challenge to the introduction of 5G services that rely on much larger bandwidths and antenna ports. The evolution of CPRI, known as eCPRI, overcomes some of the disadvantages by including some of the BBU functionality (such as frequency-time conversion) to the O-RU and introducing Ethernet, a packet-based transport technology that significantly reduces the fronthaul bandwidth, but it also presents some new challenges. It exposes some of the disadvantages of packet-based transport such a its inherent packet delay variation. Furthermore, eCPRI is not a synchronous technology and relies on synchronization techniques such as precision time protocol (PTP) [REF 8] and synchronous Ethernet (SyncE) [REF 9]. Open fronthaul interface facilitates the use of standardized multi-vendor interfaces, which paves the path to successful interoperability between O-DU and O-RU.

The O-RAN alliance adopted functional split option 7-2x where the physical layer functions are divided between the O-DU and O-RU. As shown in the following figure, in the downlink, the physical layer receives the information bits from the MAC layer and performs channel encoding, scrambling, modulation, layer mapping, precoding and resource element mapping functions, resulting in I/Q samples of an OFDM signal in the frequency domain. This complex-valued sequence is then transformed into the time domain using IFFT function. The OFDM signal is processed through digital front-end functions and is converted into the analog domain using a DAC. In this process, beamforming is performed before the IFFT in the frequency domain in the case of digital beamforming and after data converter in the time domain in the case of analog beamforming. In the downlink, split option 7-2x implements functions up to resource element mapping in the O-DU and supports O-RUs that host digital beamforming and the subsequent functions (category A O-RU) or O-RUs that host the latter functions as well as the precoding (category B O-RU). On the fronthaul, the I/Q samples of the OFDM signal in the frequency domain for each MIMO spatial stream (CAT A O-RU) or each MIMO layer (CAT B O-RU) are transmitted. To further reduce the fronthaul bandwidth, the O-RAN 7-2x split optionally allows modulation to be performed at the O-RU. This technique is referred to as *modulation compression* and technically follows the 7-3 split applied to the downlink only. In the O-RAN alliance split 7-2x, demodulation and equalization are always performed by the O-DU. In the uplink, the digital OFDM signal in the time domain is generated by conversion of the received analog signal using an ADC. The time domain signal is transformed into the frequency domain using an FFT function. The I/Q samples of the OFDM signal in the frequency domain go through resource element de-mapping, equalization, IDFT (in the case of optional DFT-transformed uplink signal), channel estimation, demodulation, and de-scrambling. The channel decoding is then performed, and the correctly extracted information bits are sent to the MAC layer following successful completion of HARQ process. In this case, beamforming is performed after the FFT in the case of digital beamforming and before ADC conversion in the case of analog beamforming. In the uplink, split option 7-2x implements resource element de-mapping and the subsequent functions in the O-DU and digital beamforming and lower functions in the O-RU. The I/Q samples corresponding to each MIMO spatial stream are transmitted over the fronthaul.

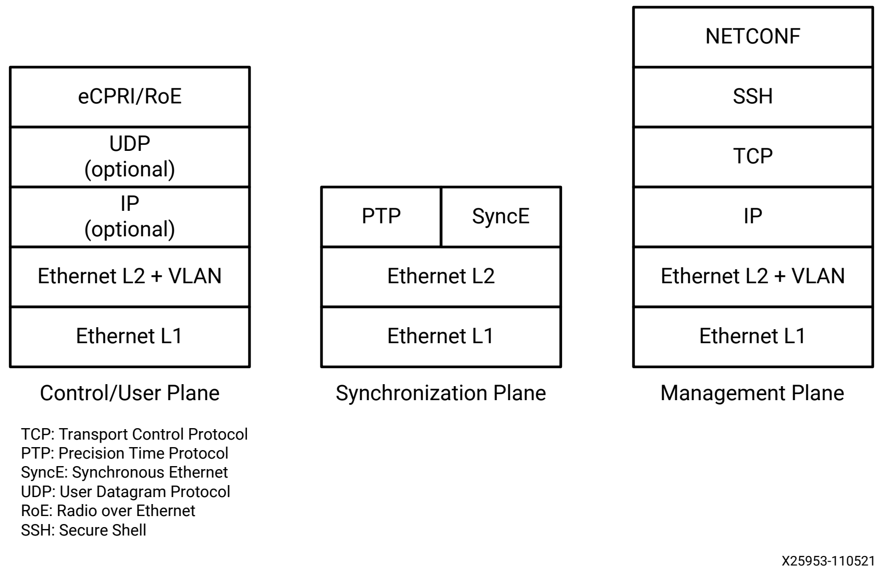
Figure 5: **Illustration of O-RAN Split Option 7-2x Downlink and Uplink Functions**



The protocol stack of user, control, synchronization, and management planes in O-RAN fronthaul are shown in the following figure. In the control/user-plane, the O-RAN fronthaul specifications support a protocol stack that transmits signals using eCPRI or radio over Ethernet (RoE) directly over Ethernet links and an optional protocol stack that transmits the signals using user datagram protocol (UDP) over IP (UDP/IP). In the synchronization plane, the O-RAN fronthaul specifications support precision time protocol (PTP) [REF 8] and synchronous Ethernet (SyncE) [REF 9]. In the management plane, the O-RAN specifications support network configuration protocol (NETCONF) over Ethernet/IP/transmission control protocol (TCP)/secure shell (SSH). NETCONF, which is specified as IETF RFC6241, is a generic protocol for managing network devices.

The *Network Configuration Protocol* is a network management protocol developed and standardized by the IETF. It was developed in the NETCONF working group and published in December 2006 as RFC 4741 and later revised in June 2011 and published as IETF RFC 6241. The O-RAN fronthaul specifications mainly utilize the data model portion of NETCONF protocols [REF 7].

Figure 6: **O-RAN User-Plane/Control-Plane/Synchronization-Plane/Management-Plane Protocol Stacks**



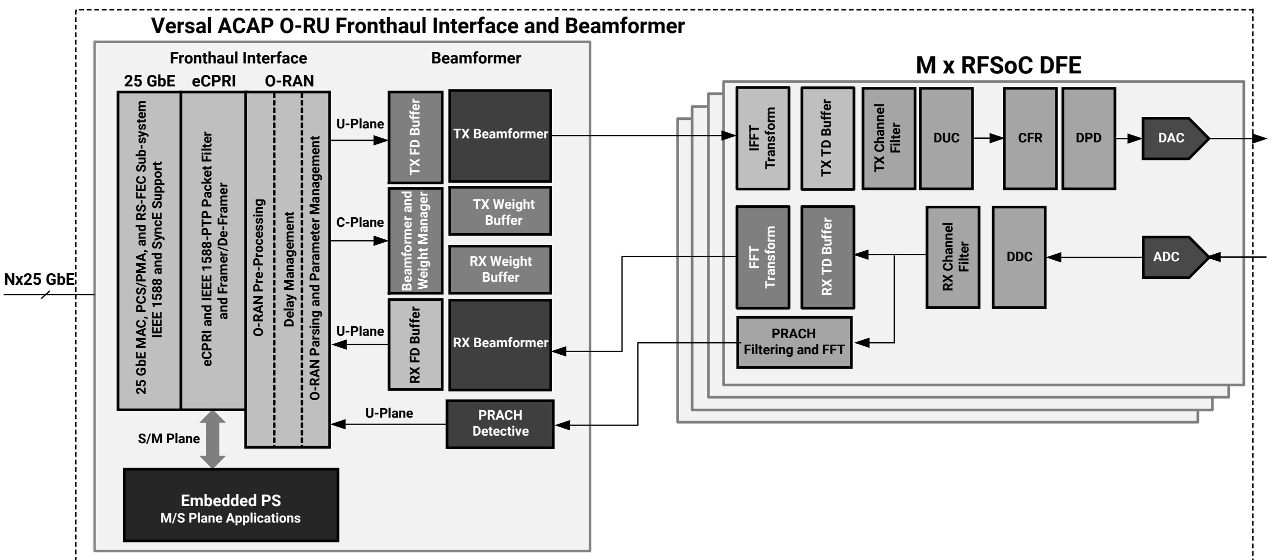
Zynq UltraScale+ RFSoC DFE

Zynq® UltraScale+™ RFSoCs are primarily designed for RF applications. They integrate key subsystems required to implement complete direct RF sampling transceivers. Significant investments have been made in the area of high-performance data converters built on advanced 16 nm FinFET CMOS technology. Each Zynq UltraScale+ RFSoC offers multiple GS/s ADC/DAC data converters. The data converters are high-precision, high-speed, and power efficient as well as highly configurable. For the latest addition to the Zynq UltraScale+ RFSoC family, the Zynq UltraScale+ RFSoC DFE, Xilinx® added dedicated support for digital functions that are often used in radio applications. The functions scale across a wide range of cellular applications starting from indoor cellular for FR1 and FR2, over macro base stations to FR1 massive MIMO. The Zynq UltraScale+ RFSoC DFE has dedicated, optimized, scalable, and parametrizable logic functions that are based on standard cell integrated blocks for compute combined with programmable logic for adapting the functions into different application requirements. The standard cell hard-blocks deliver performance typically only found in ASICs, where the programmable logical functions offer the flexibility of an FPGA. With these functions, the Zynq UltraScale+ RFSoC DFE provides twice the performance of previous RFSoC generation at half the power consumption. The logic blocks realize filtering functions, functions for digital up and down-conversion (DUC) and (DDC), interpolation and decimation, crest factor reduction (CFR), and digital pre-distortion (DPD). Other logic blocks include the fast Fourier (FFT) transformation that is often used for orthogonal frequency division multiplexing (OFDM) modulation, and now—due to the 7.2 functional split chosen by O-RAN—part of the radio.

Architecture for Massive MIMO Based on the Zynq UltraScale+ RFSoC

The following figure illustrates an O-RU architecture (analog RF processing and antenna modules are not shown) for high-power transmission in sub-7 GHz frequency range, which implements functions such as termination of O-RAN fronthaul interface, eCPRI framing/de-framing, beamforming; i.e., CAT B O-RU realization, and OFDM modulation and demodulation as well as DFE functions (DUC, DDC, CFR, and DPD) and data conversion. With an analog bandwidth of up to 7 GHz, the Zynq® UltraScale+™ RFSoC DFE can directly sample and process RF signals, thus enabling direct RF transceiver architectures, which simplify the signal conditioning and transmission/reception with fewer analog RF components. Each RFSoC DFE can process eight transmitter and eight receiver paths and when scaled by eight, the system can support 64 TRX transceiver configuration. Depending on the number of transmit/receive paths, this architecture can support 5G NR signals with occupied bandwidths of up to 200 MHz and instantaneous bandwidth of 400 MHz. For mmWave O-RUs, the same architecture can be leveraged with one or more stages of external RF mixers.

Figure 7: **Example Implementation of 16 TRX Baseband and DFE Functions on Zynq UltraScale+ RFSoCs**



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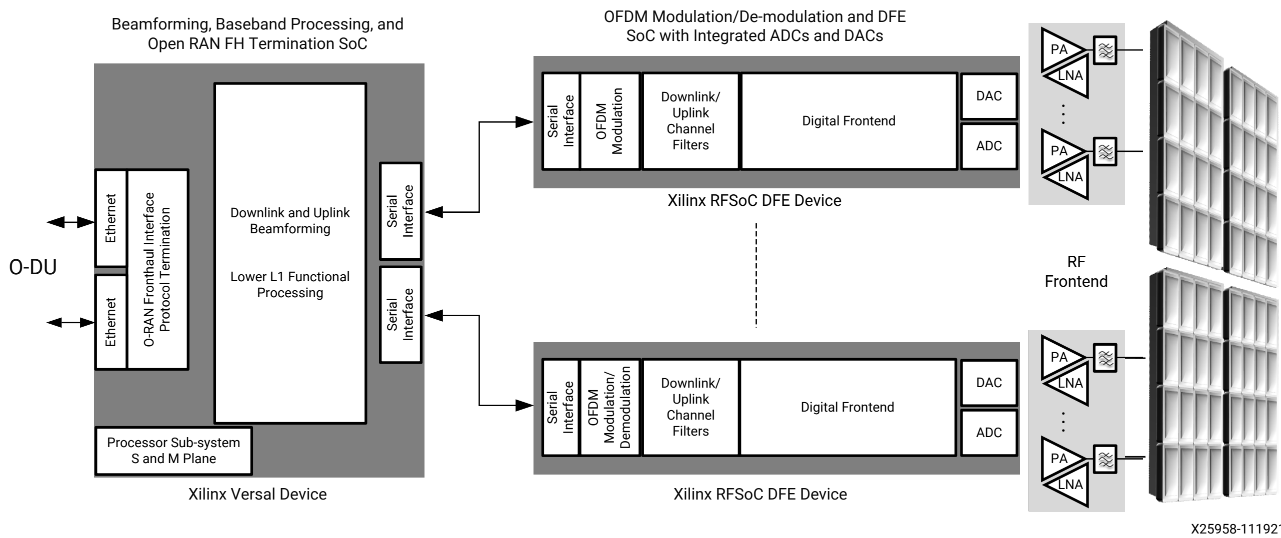
A complete functional block diagram of the proposed O-RU platform is depicted in the following figure. As shown in the figure, the functional mapping of DFE in the previous figures can be scaled based on the desired number of transceivers and the common functions such as O-RAN fronthaul termination and lower physical layer functions can be performed in another programmable SoC device. The analog RF processing as well as the antenna distribution/ aggregation module have been abstracted in the figure.

Figure 8: **Example Implementation of a 32/64 TRX Transceiver O-RU with Zynq UltraScale+ RFSoCs**



Conclusion

This white paper describes a programmable and scalable O-RAN compliant radio unit design based on direct RF sampling transceiver architecture using integrated GS/s data converters and hardware digital signal processing. The programmability and modularity of the proposed solution allow operation in different frequency bands using suitable RF processing and antenna modules with the same fronthaul termination and digital signal processing modules, resulting in radio unit platforms that can be configured for different use cases and deployment scenarios. The latter features are crucial for the success of 5G and beyond systems which require support of various applications in a wide range of deployment options. The Xilinx Zynq UltraScale+ RFSoC DFE is the ideal direct RF sampling transceiver platform for massive MIMO applications, delivering ASIC-like performance while keeping the flexibility of an FPGA.

References

These documents provide supplemental material useful with this guide:

1. *3GPP TS 38.104, NR; Base Station (BS) Radio Transmission and Reception (Release 17)*, September 2021.
2. *CPRI Specification v7.0, Interface Specification*, Common Public Radio Interface (CPRI), October 2015.
3. *eCPRI Specification v2.0, Common Public Radio Interface: eCPRI Interface Specification*, May 2019.
4. Sassan Ahmadi, *5G NR: Architecture, Technology, Implementation, and Operation of 3GPP New Radio Standards*, Academic Press, June 2019.
5. *O-RAN-WG1-O-RAN Architecture Description*, v1.00, Open RAN Alliance, February 2020.
6. *O-RAN.WG7.DSC.0-v2.00, O-RAN White Box Hardware Working Group Deployment Scenarios and Base Station Classes*, Open RAN Alliance, June 2020.

7. *O-RAN-WG4.CUS.0-v7.00 Technical Specification, O-RAN Fronthaul Working Group Control, User and Synchronization Plane Specification*, July 2021.
8. *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems* (IEEE 1588-2019).
9. *Timing Characteristics of a Synchronous Equipment Slave Clock* (ITU-T G.8262)

Revision History

The following table shows the revision history for this document.

Section	Revision Summary
2/01/2022 Version 1.0	
Initial release.	N/A

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