

Evaluating Cloud RAN Implementation Scenarios

Stringent timing requirements in the RAN pose challenges when virtualizing network functions

Overview

Today's mobile operators are facing widespread challenges as exploding smart phone usage is putting unprecedented pressure on networks. The staggering growth in mobile data traffic, predicted to increase 11-fold between 2013 and 2018,¹ has mobile operators redoubling their efforts to increase network capacity. However, the cost of building, operating, and upgrading the radio access network (RAN) is becoming increasingly expensive and unwieldy, while the average revenue per unit is flattening.

At the same time, the telecom industry is embracing network functions virtualization (NFV) as a means to reduce cost and complexity, and speed up the deployment of new applications and services. NFV is also being applied to the access network with RAN functions moving from macro and pico eNodeBs to centralized general-purpose servers, an architectural approach called Cloud RAN (C-RAN).

This paper explains the applicability of NFV concepts to RAN functions, and examines the challenges and tradeoffs associated with four different C-RAN implementation scenarios with varying amounts of centralized functionality.

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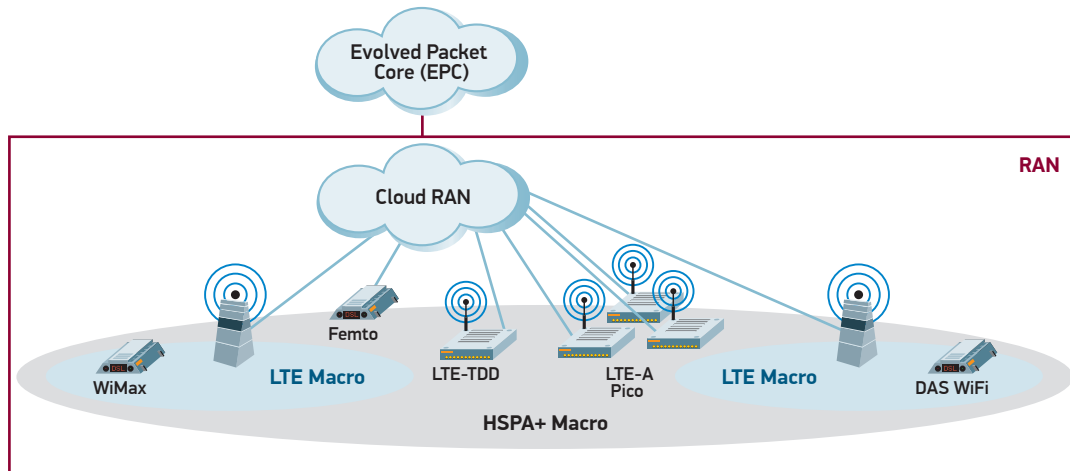


Figure 1. Options in Radio Access Network

RAN Topologies

In an ever-evolving world of wireless communications, the operator community is constantly challenged to integrate new radio access technologies, solve the always-on connectivity problem, increase throughput with better QoS, scale with increasing throughput demand, and manage a large number of complex devices. The whole network is under pressure to meet these requirements, especially in the RAN, which handles the most critical of the resources—the air interface—and is one of the highest priorities.

End-user devices must ultimately connect to wireless core networks via a radio interface, which is the function of macro base stations, small cells, and remote radio heads (RRHs) that sit out in the RAN. The evolution of the RAN has led to a heterogeneous network (HetNet) with various ways to provide coverage, as depicted in Figure 1. Large network operators typically employ a mix of topologies since their networks are far from homogeneous.

Macro Cells: The prevalent workhorse in the RAN for most network operators, the base station (or eNodeB in LTE) has vast responsibilities, including radio resource management (RRM), radio environment monitoring (REM), and self-organizing network (SON). Due to their relatively high cost and power consumption, base stations are typically located where there are large numbers of subscribers in a cell site ranging a few kilometers.

Small Cells: Network operators can cost-effectively increase coverage density with small cells, which usually have a range of tens of meters to two kilometers. Performing all base station functions, small cells can serve a wide variety of locations, including urban, rural, and in-building. For instance, several small cells could be deployed in a large metro shopping mall: one small cell in each long corridor. The small cells themselves are classified as indoor (femtocells, enterprise small cells), and outdoor small cells (e.g., metrocells).

Remote Radio Heads: Designed to be compact and low power, remote radio heads (RRHs) connect tower antennas to the C-RAN via optical fibre, offering network operators an easy-to-deploy and flexible solution for increasing coverage.

Both macro and small cells have complete protocol and radio support. They may engage in coordinated transmission and reception to support aggregated carriers or multipoint schemes. As studied by multiple research organizations, there can be scalability issues when the method to address growing user demand is to increase the number of macro and small cells. This approach also poses practical challenges with respect to network planning, cell site development, power usage, increased CapEx and OpEx, and heterogeneous network management.

C-RAN architecture, which centralizes most of the RAN components, can solve some of the aforementioned problems, but also presents some new challenges.

Evolution of C-RAN

The C-RAN brings the flexibility to decouple the radio and RF from the base band processing and allocates the resources, when needed, from a centralized pool, thus enabling better use of processing power and improved coordination between base stations. The next generation deployments will combine the ease of adding small cells to increase capacity with the ‘cloudification’ of the RAN via C-RAN.

Leaders in C-RAN development, China Mobile and Alcatel-Lucent demonstrated an LTE RAN Baseband Unit (BBU) based on NFV principles at Mobile World Congress 2014 in Barcelona.² China Mobile has been developing C-RAN systems since 2009 and identified the key benefits of C-RAN to operators in a white paper:³

- Energy savings
- TCO reduction
- Improved spectral efficiency
- Improved resource efficiency
- Services on the edge enablement

At the same time, ETSI has been working to standardize NFV concepts, including on a C-RAN proof-of-concept (PoC) project. A final PoC report with results and findings is expected during the summer of 2014.

These industry activities demonstrate that C-RAN is being seriously considered as an architectural option. However, before C-RAN is ready for deployment, a number of challenges must be solved—the most significant of them being strict latency requirements. For instance, LTE specifies a one millisecond maximum transmission time interval (TTI) between the user entity (UE) and LTE RAN (eNodeB). In a typical baseband

Turnkey LTE Small Cell Solution

Radisys’ Trillium® TOTALeNodeB software is a deployment-proven small cell solution that dramatically simplifies the development and integration of LTE small cells while cutting the typical product development time in half. It enables customers to leverage one software solution that can support all small cell deployments across the network, from residential cells that support up to eight users to picocells that support 100+ users. The scalability and flexibility of the architecture enables rapid deployment as well as sets a baseline for future evolution such as Cloud based RAN.

Trillium TOTALeNodeB software runs on leading small cell SoCs, including the Intel® Transcede SoCs, which are dual-mode capable devices that support concurrent 3G and LTE operation. A number of small cell vendors, including Qucell, Juni Korea, and Dongwon T&I, have integrated the Radisys Intel-based solution into their product portfolios. These companies have worked with Radisys and Intel to deploy commercial small cells for major service providers, such as South Korea-based Korea Telecom (KT).

pooling C-RAN architecture, cell sites only have an antenna or RRH, and the cloud contains all the base station hardware and software. In this particular scenario, it will be necessary to use an ideal fronthaul technology, as indicated in a 3GPP technical report⁴ that discusses ideal and non-ideal approaches. C-RAN implementations can also use CPRI as the fronthaul solution.

NFV and C-RAN

The following analysis applies NFV concepts to LTE C-RAN architectures, thus enabling options that go beyond the baseband pooling functionality proposed by typical C-RAN architectures. In addition, four C-RAN implementation scenarios are discussed, as well as their associated advantages and disadvantages, making it easier for base station designers to compare and contrast them. The solution examples are for LTE networks; however, the same concepts can be used in UMTS, LTE/UMTS dual mode, LTE/Wi-Fi, and LTE/UMTS/Wi-Fi HetNet scenarios.

It should be noted that this paper presents views that are conceptual in nature, and Radisys and co-authors will furnish actual reports in the future.

NFV Architecture

ETSI NFV working groups are in the process of completing the NFV reference architecture,⁵ which, as of May 2014, is depicted in Figure 2. Key elements of the framework are discussed in the following sections.

Virtual Network Functions (VNF)

When NFV principles are applied to the RAN, the most significant change is that network functions will be virtualized and run in virtual machines (VMs); hence, they are called virtual network functions (VNFs). Groups and subgroups of functions can become VNFs that during their lifecycle may be listed, created, queried, updated, deleted, rebooted, and resized.

The granularity of the VNF functions is the designer's prerogative. A more granular solution provides greater control over the system functions and increased abstraction between functionalities. For example, on the RAN side, running Uu interface protocols (connecting UEs and eNodeBs—MAC, RLC, PDCP, RRC) and L2 transport protocols (GTP-u, SCTP) in two different VMs provides the following flexibility:

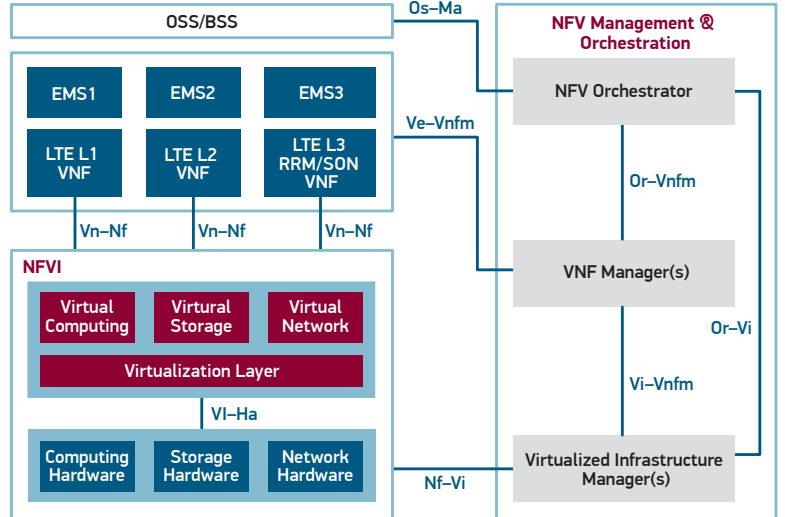


Figure 2. NFV Software Architecture Scope within the NFV Reference Architecture Framework

- **Manage the Number of Users and Throughput Independently:** Uu interface protocols handle the transmission time interval (TTI) processing in eNodeB, and processing overhead increases as the number of user equipment (UEs) to be handled per TTI increases. To accommodate higher active user requirements, processing capacity of Uu interface protocols VMs can be increased independently. The aggregate cell throughput remains constant for any number of users in the cell. Hence, the other VMs handling the L2 transport protocols will not need capacity enhancement.
- **Improve Hardware Accelerators Usage:** Uu interface protocols can be assigned to computing platforms with specific hardware accelerators for compute-intensive workloads, such as over-the-air (OTA) security (e.g., AES, Snow3G, and Zuc) and robust header compression RoHC. At the same time, L2 Transport protocols can run on platforms that have hardware offload for GTP header addition/deletion and fast-path TCP/IP implementations to reduce data path transport latency. By splitting Uu interface protocols and L2 transport protocols, these workloads could be assigned to computing platforms with accelerators that can significantly increase their performance.

VNF	Group	Subgroups
LTE L3, Radio Resource Management (RRM), Self-Organizing Network (SON)	LTE L3 Protocols and Call Control Finite State Machines (FSMs)	Control Protocols–Radio Resource Control (RRC), S1 Application Part (S1AP), X2 Application Part (X2AP) Transport Protocols–Streaming Control Transport Protocol (SCTP), TCP/IP
	Radio Resource Management (RRM)	Admission Control–Call, radio bearer Mobility Control–Inbound, outbound, core network signalling reduction QoS Control–Backhaul, radio interface Overload Control–Local overload control based on CPU, memory, max number of active users, max number of users, transmission time interval (TTI) Overload Control–S1 Flex, MME overload Carrier Aggregation–Coordinated Primary Cell (PCell) and Secondary Cells (SCell(s)) Management Coordinated Multipoint–Joint scheduling, joint processing Multi-Operator Core Network (MOCN)–Backhaul and radio resources management Load balancing across different cells
	Self-Organizing Network	Radio Environment Monitoring–Physical Cell Identity (PCI), UL/DL E-ARFCN selection, power setting Automatic Neighbor Relation Management–Add/delete/modify neighbor Mobility Robustness (MRO) Interference Management–Frequency domain, time domain, blanking patterns
	Self-Optimizing Network	PCI Collision Handling Frequency Jamming Handling Dynamic Power Control
Operations, Administration and Maintenance (OAM)		OAM Transport–TR-069/SNMP/XML Data Model–TR-196, TR-196i2 Alarms Reporting Statistics Collection
LTE L2	LTE L2 Protocols	Uu Interface Protocols–Medium Access Control(MAC), Radio Link Control(RLC), Packet Data Convergence Protocol(PDCP) L2 Transport Protocols–GPRS Tunnelling Protocol(GTP), UDP/IP
	MAC Scheduling	Scheduler Types–Round Robin(RR), Proportional Fair Share(PFS), Frequency Selective Scheduler Functions–Common, UL or DL scheduling Scheduler Functions–Cell- and UE-specific scheduling Scheduler Domains–FDD, TDD
LTE L1	L1 Functions	CRC, rate matching, channel coding, channel interleaving, segmentation/concatenation Channel-specific functions–BCH, HARQ, RACH, DL-SCH, CFI, UL-SCH, DCI, PUCCH

Table 1. Possible VNFs, groups, and subgroups for C-RAN

Making VNFs highly granular can help operators manage capacity with greater precision, which is especially beneficial when VNFs must handle large capacities as part of a very large C-RAN that services thousands of users, implements multiple technologies, and covers a large geography. On the other hand, overly granular VNFs could increase administrative and management overhead for the

system. An enterprise cloud may not need highly granular VNFs, but instead could just create three separate VMs for Layer 1 (L1), Layer 2 (L2), and Layer 3 (L3) functions.

Possible VNFs, groups, and subgroups outlining the scope of required Cloud RAN functionality are listed in Table 1 and shown in Figure 3.

Scheduling VNFs

For LTE networks, medium access control (MAC) scheduling for radio resources on the Uu interface is the most time-critical function. Each eNodeB has its own scheduler that handles common cell- and UE-specific radio resources. The scheduler dynamically schedules UEs that are connected and/or in active state. When scheduling UEs, the scheduler takes into account the available bandwidth, number of component carriers (CCs), common resource needs, UE bearer priority as per QoS class identifier (QCI), UE pending buffer status in UL and DL, channel quality reports, etc. The scheduling VNF in C-RAN architecture enables new capabilities, such as:

- Improved Resource Utilization:** Storage and compute segments of the scheduler operation can be segregated. All cell scheduler contexts, UE scheduler contexts, cell states, and UE states can be maintained in the virtual storage irrespective of the cell the UE belongs to. Compute resources for the DCI, PUCCH, and HARQ handlers, etc can be invoked with appropriate UE contexts; thus, compute scheduler VNFs become independent entities that any cell can use.
- More Robust Carrier Aggregation:** Per the carrier aggregation feature in the 3GPP Release 10 Advancements, multiple carrier components (CCs) can be used to service a single UE. While this feature increases the overall throughput by as much as 3 Gbps, it also mandates very close synchronization between participating CCs. But this imposes a strict requirement on a UE, which now must tolerate a relative propagation delay difference of up to 30 microseconds among the component carriers to be aggregated.

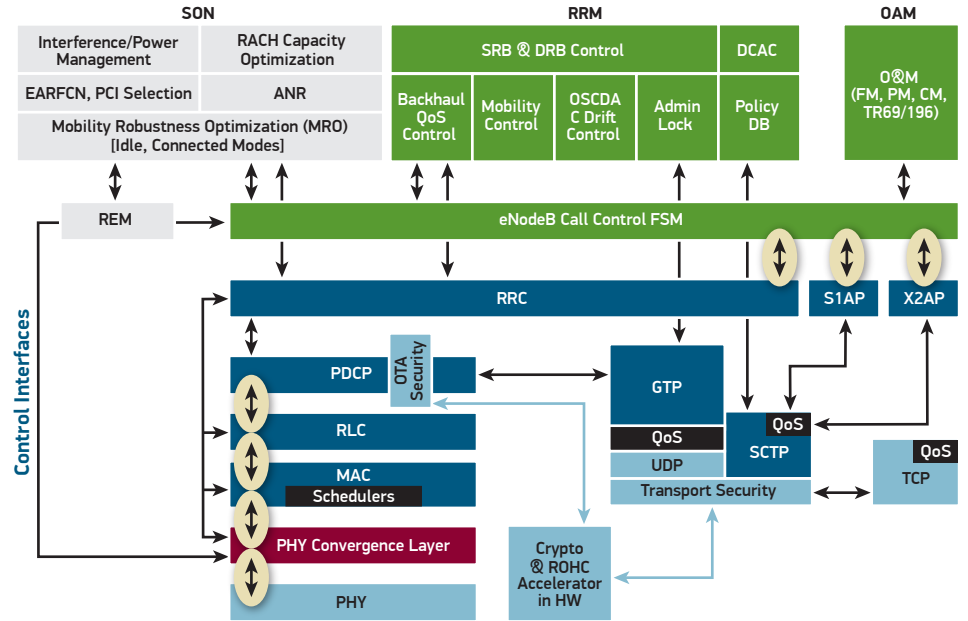


Figure 3. Cloud RAN Functionality

A typical small cell platform supports one carrier, has its own on-board reference clock, and uses methods like PTP, NTP, and SyncEther to discipline its frequency clock at regular intervals. Since small cells are rather independent, there is a high probability of two neighboring cells drifting apart, thus making individual small cell based carrier aggregation deployment complex. Conversely, C-RAN co-locates all compute resources, so it is relatively easy to have single clock reference for all participating CCs, which eliminates clock skew.

- Increase Efficiency Through Consolidation:** Implementing a carrier aggregation feature may require joint scheduling for all participating CCs (up to five maximum). Instead of separate physical form factors, which may be geographically distributed, C-RAN architecture enables a single platform to host all the CCs, and this co-location greatly simplifies joint scheduling.

Control Plane VNFs

The LTE eNodeB uses control plane protocols to communicate broadcast information, UE states, UE connection messages, measurement start/stop, mobility decision, etc. Radio resource control (RRC), S1 Application Protocol (S1AP), and X2 Application Protocol (X2AP) use Abstract Syntax Notation One (ASN.1) encoding and decoding to communicate with UE, MME, and neighboring eNodeBs, respectively. C-RAN allows for the use of a control plane protocol that is relatively less risky through virtualization, which can provide added benefits:

- **Lower Backhaul Costs:** Control protocols are not in the critical path of L2 processing (e.g., TTI), so it is possible to host them in another location with less expensive backhaul technology.
- **Lower Cost Compute Resources:** L3 control protocol processing does not need specialty hardware accelerators, and consequently, it makes sense to host them on economical general-purpose compute resources, separated from L2/L1 processing that typically needs hardware accelerators.
- **Improved Resource Scaling:** L3 control protocol VNFs can be created and managed as the number of radio resource control (RRC) idle and RRC connected users increase in the system. The scaling of L3 control protocol VNFs can be independent of L2 VNF scaling.
- **Higher Resource Utilization:** Storage and compute segments of the control plane operation can be segregated. All cell contexts, UE contexts, cell states, and UE states can be maintained in the virtual storage irrespective of the cell the UE belongs to. The compute segments (ASN.1 encoder/decoder) can be invoked with appropriate UE and cell contexts, thus compute control plane VNFs become independent entities to be used by any cell.
- **Enhanced Availability:** For C-RAN implementations, it is important to ensure high availability to allow the control plane to maintain UE states. With control VNFs as deployment modules, it is relatively easy to maintain active and standby states for each cell and/or carrier:

- active : active
- active : standby
- m x active : n x standby

- **Flexible Load Balancing:** In C-RAN architecture, S1 connections from all cells can be aggregated, thus offering S1 gateway-like functionality in the same package. Along with S1 aggregation, a C-RAN can also handle non-UE specific signaling, such as intelligent overload control. It may distribute the RAN load across the available cells or MMEs whenever a cell or MME becomes overloaded.

Data Plane VNFs

In an LTE eNodeB, the GTP-u protocol supports data path communications to/from the core network and handles the cell's aggregate throughput, making it a critical transport module. GTP-u is a transport protocol responsible for tunnelling user data across S1, S5/S8, etc. interfaces.

A data plane VNF will use the GTP-u protocol and corresponding handling mechanisms. A transition to C-RAN will virtualize the GTP-u module, which can provide the following benefits:

- **Software Reuse:** Assuming data plane compute segments can work on specific UE contexts, the same GTP-u VNF should work with multiple cells.
- **Improved Scalability and Resource Utilization:** Data plane VNF instances can be increased or decreased to respond to C-RAN throughput demands. Assuming the same GTP-u VNF supports multiple cells, the VNF manager will be able to balance the traffic load across data plane VNFs as needed.

Radio Resource Management VNFs

C-RAN architecture allows for a common control plane and radio resource management (RRM), which facilitates load balancing across cells, sectors, carrier components, and processor capacity. In addition, this centralization simplifies tasks such as priority and QoS handling, multi-operator core network (MOCN) support, and overload control. A RRM VNF could support the following functions:

- **Admission Control (AC):** New call admission or new bearer admission can be handled more efficiently in C-RAN than in standalone eNodeBs. The co-located AC function shall have the knowledge of the cell/sector loading of all deployed cells. Hence, while admitting a new call/bearer or admitting handed over calls with bearers, C-RAN admission control function can use the cell that is less loaded. Having AC in VNFs will allow decision making to be hosted in the VNF while actual eNodeB call control applications can execute the decision.
- **Mobility Control:** The RRM VNF shall have the cell loading, neighbor cell information, measurement information of all cells deployed, and all active UEs reporting measurements. Thus, extracting mobility in RRM VNF will allow RRM to have the knowledge of a much larger radius than a standalone eNodeB. Specialized mobility robustness algorithms (MROs) can evolve for C-RAN to make better mobility decisions.
- **QoS Control:** QoS control can become a separate VNF to handle the backhaul usage for all cells, baseband processing (when centrally pooled) for all UEs, and subsequently the bearers of QoS. A QoS VNF can run algorithms that include all the bearers as the user and whole backhaul pipe as the resource. Each eNodeB need not run a backhaul QoS scheduler. A QoS VNF can also work closely with the MAC scheduler to map the backhaul QoS to the MAC QoS and allow baseband processing resources per the combined algorithm.
- **Overload Control:** The C-RAN shall have the knowledge of all CPU usage, memory usage, the maximum number of active users, and the maximum number of users/TTI per cell deployed. If one cell is overloaded, a call admission and mobility control decision can be influenced by the load information available centrally. The RRM VNF may admit the call in a less loaded cell or decide to hand it over to a less loaded cell.
- **Carrier Aggregation:** Coordinated PCell and SCell(s) management via LTE-A carrier aggregation (CA) mandates close synchronization across component carriers. Also, 3GPP allows for dynamic addition and deletion of secondary cells (SCells). Having the

RRM VNF handle the synchronization and creation/deletion/modification of SCells will allow operators to have centralized decision making. This will also reduce the overhead on each eNodeB related to processing CA algorithms. Since the RRM VNF shall have control over all cells and measurement reports from all UEs, it will be easier to run algorithms that can choose the right SCells for a UE.

- **Coordinated Multipoint:** C-RAN architecture provides significant joint scheduling and processing benefits to coordinated multi-point operation by co-locating all participating cells. The synchronization needed across the cells is handled by using the same clock source for most or all of the participating cells. Joint scheduling becomes easier if the MAC schedulers are centralized since the cell/sector schedulers share power usage, channel quality information, and blanking pattern to efficiently schedule all cells/sectors.
- **Multi-Operator Core Network (MOCN):** The RRM VNF is well-positioned to handle multiple operators' scenarios. MOCN functionality requires the available radio resources to be distributed among UEs/bearers from multiple operators. C-RAN architecture, having control over multiple cells/sectors, allows operators to converge on a single point, and the MOCN VNF can provide the required QoS by operator bearers based on operator priority, weightage, cell loading, and operator UEs channel quality.

Self-Organizing and Self-Optimizing Network (SON) VNFs

C-RAN architecture supports coordinated SON strategies, mobility load balancing, coordinated blanking patterns, coordinated power control and capping and close-time synchronization. The C-RAN can adopt a centralized SON server approach, which is responsible for SON decision making for all participating cells at a central location, simplifying self organization and self optimization. A hybrid SON server with distributed intelligence is not required. Unlike a cluster of small cells or multi-sector macro eNodeBs, the C-RAN will have control over a much larger deployment area, allowing the operator to manage SON policies in a much less disruptive manner.

- **Automatic Neighbor Relation (ANR) Management:** The C-RAN can use the collective neighbor information available from all deployed cells to make neighbor management decisions. Based on neighbor and location measurement reports, the C-RAN SON server can assign the right neighbors to all cells.
- **Mobility Robustness:** Likewise, the ANR C-RAN can avoid too-early or too-late mobility decisions using the collective cell knowledge and UE positions.
- **Interference Management:** The C-RAN can make centralized decisions for the DL and UL E-ARFCNs, thereby eliminating the interference across C-RAN controlled cells. It can also decide the frequency reuse (soft or fractional) for all cells, minimizing the interference levels across deployed cells. The C-RAN can also decide the almost blank subframe (ABS) patterns for all cells (if the policy mandates the use of time domain ICIC) centrally. Such centralized decision making, together with close time synchronization across all cells, will deliver a very efficient interference management system.
- **PCI Collision Handling:** PCI collisions are not an issue with C-RAN implementations, as PCI allocation for cells will be done at the central SON server.

NFV Orchestrator

The NFV orchestrator maintains the network service (NS) catalog and VNF catalog for all on-boarded C-RAN services and packages. ETSI is in the process of defining Management and Orchestration (MANO) descriptor files to maintain the database of all services and VNFs.

Element Management System (EMS) and OSS/BSS

C-RAN architecture should be able to incorporate existing element management system (EMS) and OSS/BSS components. The C-RAN shall be able to use a single transport using SNMP, TR-069 or XML, and all cells controlled by C-RAN shall not need to maintain the OAM transport. The OAM transport shall be used to report the following:

- Alarms reporting
- Statistics collection

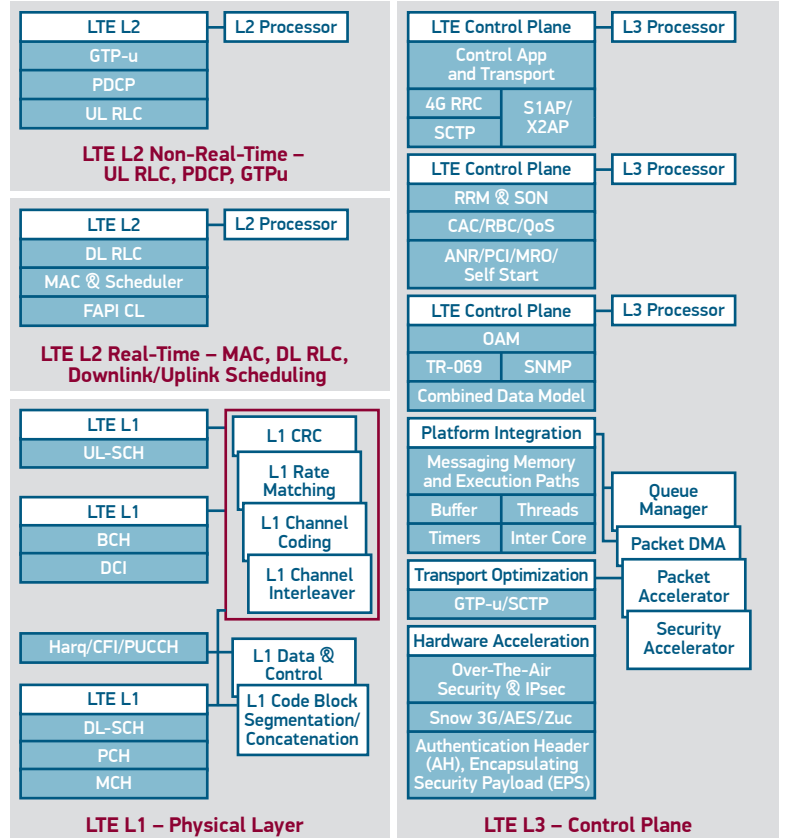


Figure 4. Main RAN Network Functions Partitioned into Four Subgroups

C-RAN Functional Architecture

This section outlines four possible C-RAN implementation scenarios that partition RAN network functions between cell sites and the C-RAN in different ways. Figure 4 shows how the functions can be divided into four subgroups:

1. LTE L1—Physical Layer
2. LTE L2 Real-Time—MAC, DL RLC, Downlink/Uplink Scheduling
3. LTE L2 Non-Real-Time—UL RLC, PDCP, GTPu
4. LTE L3—Control Plane

In addition, the remote radio head (RRH) supports other functions, including analog-to-digital, digital-to-analog and up/down conversion. It also performs operation and management functions and provides the optical interface to connect to the C-RAN.

Four C-RAN Implementation Scenarios

RAN functions can be split up between the cell site and the C-RAN in different ways; illustrating this point, Figure 5 shows four partitioning scenarios that range from centralizing all subgroups in the C-RAN to only centralizing the L3 network layer:

- **Scenario #1**—All subgroups centralized in the C-RAN
- **Scenario #2**—All subgroups centralized in the C-RAN except for the L1 physical layer
- **Scenario #3**—All subgroups centralized in the C-RAN except for the L1 physical layer and real-time L2 downlink/uplink scheduling
- **Scenario #4**—Only the L3 network layer is centralized in the C-RAN

Scenario #1—All Subgroups Centralized in the C-RAN

This is the classic realization of cloud RAN architecture, with all network functions (except RRH functions) virtualized and running on centralized, general-purpose servers, as shown in Figure 5. The VNFs are assigned to the most appropriate processor and have access to the hardware accelerator that will most efficiently execute the associated LTE L1-L2-L3 functionality.

This scenario does not restrict the granularity to which VNFs can be broken down. External antennas and RRHs are used to distribute the radio signals at the cell site. The distance from centralized VNFs and cell sites are variable based on the chosen fronthaul technology.

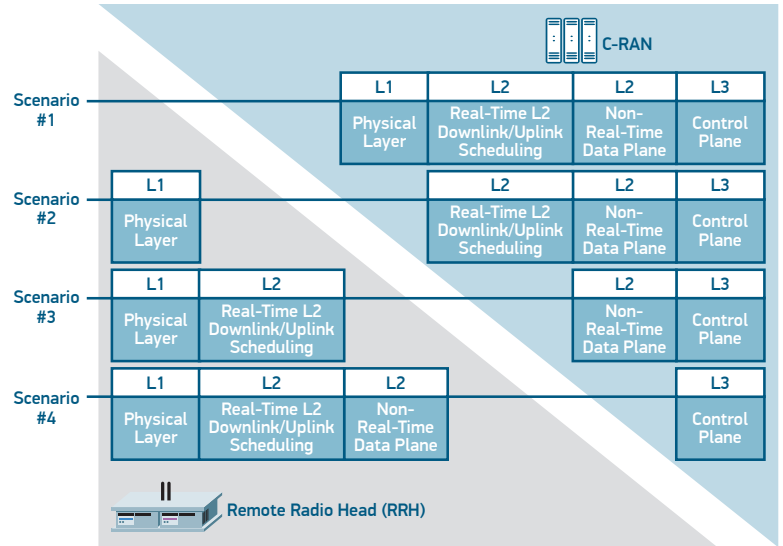


Figure 5. Four C-RAN Implementation Scenarios

Categorization of Non-Ideal Backhaul			
Backhaul Technology	Latency (One way)	Throughput	Priority (1 is the highest)
Fiber Access 1	10-30ms	10M-10Gbps	1
Fiber Access 2	5-10ms	100-1000Mbps	2
Fiber Access 3	2-5ms	50M-10Gbps	1
DSL Access	15-60ms	10-100Mbps	1
Cable	25-35ms	10-100Mbps	2
Wireless Backhaul	5-35ms	10-100Mbps typical, maybe up to Gbps range	1

Categorization of Ideal Backhaul			
Backhaul Technology	Latency (One way)	Throughput	Priority (1 is the highest)
Fiber Access 4 (NOTE 1)	Less than 2.5 us (NOTE 2)	Up to 10Gbps	1

Note 1: This can be applied between the eNodeB and the remote radio head.

Note 2: The propagation delay in the fiber/cable is not included.

Table 2. 3GPP Findings about Ideal and Non-ideal Connections

- **Advantages:** As previously discussed, C-RAN provides a path to CapEx/OpEx reduction, easy resource scaling, higher resource utilization, and flexibility through VNFs. The virtualized C-RAN also enables unused servers to be powered down to save energy when traffic demand is below peak.
- **Disadvantages:** Given the strict latency and throughput requirements between the L1 and radio frequency integrated circuit (RFIC), C-RAN can be an expensive solution. Due to the strict one millisecond transmission time interval (TTI) requirement of the LTE physical layer, the operator has to choose the best fibre access technology for the L1 to RFIC interface. The operator also needs to make sure the distance between the L1 and the RFIC allows latency requirements to be met. 3GPP studied the ideal and non-ideal connections, and their findings⁶ are reproduced in Table 2. Moreover, some small cells will see Common Public Radio Interface (CPRI) as the L1 to RRH connection technology.

Note: The industry is also discussing the possibility of adding another term fronthaul for the connection between the RRH and baseband.

Scenario #2—All Subgroups Centralized Except for the L1 Physical Layer

This implementation scenario is the same as the previous scenario #1 except the L1 physical layer functions are executed near the cell site. Consequently, L1 functions are not virtualized, though L2-L3 functions can be virtualized in the C-RAN. In this scenario, L2 processing can be one to two milliseconds off from the actual subframe number/subframe (SFN/SF) SFN/SF at L1. The ability to complete L2 processing, including the L2-L1 interface latency within one millisecond, is still critical. However, L2 has a small window to manage the time criticality. The communication between L1 and L2 is left to designers, but a best possible fronthaul access will be required to maintain operational state for a large distribution area.

- **Advantages:** This implementation scenario is well-suited for enterprise, mall, stadium, etc. deployment scenarios where the latency between L2 and L1 can be kept under control by using less expensive fronthauls, like fibre access 4 (table 2) or gigabit Ethernet for manageable distances. All L2, L3, RRM, SON, and OAM functions can be deployed as VNFs. Present day small cell platforms (hosting only the L1) fitted with daughter RF cards can be used at cell sites, possibly eliminating the need for RRH platforms.
- **Disadvantages:** The latency requirements are critical and similar to Scenario #1, thus the same disadvantages apply (see prior section). In addition, L1 is located in the cell site, eliminating the possibility for an L1 VNF and the associated benefit previously discussed.

Scenario #3—All Subgroups Centralized in the C-RAN Except for the L1 Physical Layer and L2 Real-Time Processing and Downlink/uplink Scheduling

Continuing the trend of moving RAN functions from the C-RAN to near the cell site, this scenario relocates L2 real-time downlink/uplink scheduling to near the cell site, in addition to the physical layer. This puts the time critical part of the eNodeB (Scheduler, RLC DL, MAC DL, L1) closer to the cell site, and leaves the rest of L2 (RLC UL, PDCP, GTP) and L3 in the C-RAN.

The transmission time interval (TTI) processing path, specifically L2 downlink/uplink scheduling path, is an extremely time critical operation in LTE networks. The user entity (UE) needs physical downlink control channel (PDCCH) allocation, hybrid ARQ (HARQ) responses, etc. to be within the TTI boundary. Therefore, it is most critical to meet the latency requirements in the downlink (DL) direction. While in the uplink (UL) direction, L2 is tolerant enough to allow one TTI delay for UL data and control to reach L2.

- **Advantages:** This architecture reduces the dependency on expensive backhaul technology. Operators can meet the aggregate cell throughput requirements using a number of backhaul technologies, such as gigabit Ethernet, microwave links, and Wi-Fi.
- **Disadvantages:** L1 and L2 downlink/uplink scheduling functions will not be virtualized and provide the same benefits as described in scenarios 1 and 2. L2 is divided into time-critical and time-non-critical parts, thereby increasing the level of non-3GPP specific communications between these two entities.

Scenario #4—Only the L3 Network Layer Is Centralized

In this scenario, only L3 functions are centralized in the C-RAN, and all L1 and L2 functions are executed near the cell site. This scenario is the easiest of the four to deploy in the near term because it eliminates the need for custom backhaul technology capable of meeting timing requirements, and it separates the functions that are in logically distributed and centralized locations.

- **Advantages:** This scenario eliminates the need to deploy expensive backhaul technology because the C-RAN is just responsible for the control signaling since the cell site handles the data path, including the GTP-u protocol processing.
- **Disadvantages:** There is no opportunity to virtualize L1 and L2 functions, and as demand grows, the need for more cell sites will increase.

Application-Ready C-RAN Platform

Radisys, Wind River, and Intel have developed a carrier-grade, application-ready platform, shown in Figure 6, that is specially designed to maximize the speed of network functions running in a virtualized environment. This is critical because RAN deployments require equipment that can handle a frame within one millisecond (1000 microseconds). Making this difficult

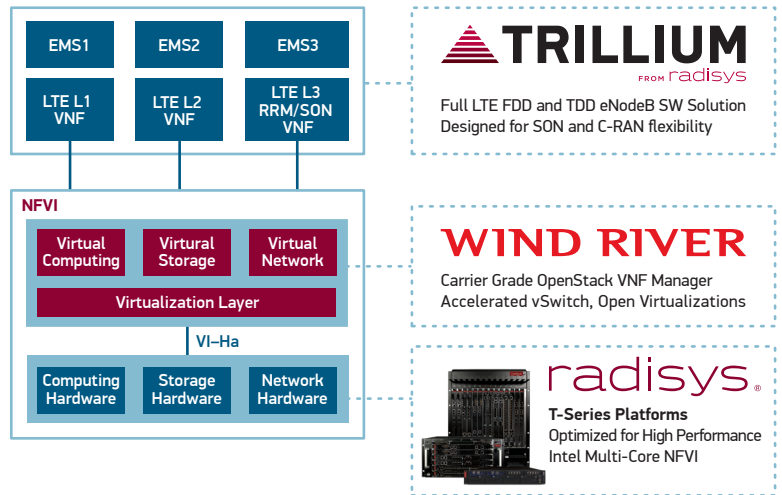


Figure 6. C-RAN Application-Ready Platform

to achieve, the interrupt latency of standard KVM solutions can be as high as 900 microseconds, which does not leave much time for the L1/L2/L3 application to run. In contrast, this collaborative solution greatly improves upon the interrupt latency of standard KVM solutions by guaranteeing a worst case interrupt latency of 10 microseconds. In fact 99.9999 percent of the time, the interrupt latency is below 9 microseconds, which means applications have 990 microseconds to execute.

The main platform components are described in the following:

Open Virtualization Profile Features

Open Virtualization Profile (OVP) integrates a range of technologies and techniques to deliver adaptive performance, interrupt delivery streamlining and management, system partitioning and tuning, and security management. The adaptable, secure, and performance-oriented base software is augmented via cluster and cloud services, and it supports a heterogeneous collection of hosts and guests. OVP also produces a set of packages that can be used on non-Wind River Linux distributions, allowing integration with third-party or Wind River Linux orchestrated networks.

In order to deliver deterministic performance, OVP employs a number of techniques that can be divided into three broad categories:

1. **Interrupt Delivery:** The code paths are streamlined to deliver interrupts to the associated KVM guest OS as fast as possible.
2. **Interrupt Handling:** Interrupts are acknowledged quickly, and system priority is given to the KVM guest after an interrupt arrives.
3. **CPU Isolation:** The guest OS can run uninterrupted before and after interrupt delivery because sources of cross CPU interference are minimized or eliminated.

Wind River Carrier Grade Communications Server

Wind River Carrier Grade Communications Server is a commercial, carrier-grade, virtualized software platform. The solution is designed specifically for network functions virtualization (NFV) deployment and seamlessly integrates with existing networks. It provides OpenStack support out of the box with agents for compute, networking, block storage, object storage, orchestration, and dashboard resources. Included is carrier-grade middleware for operations, administration, maintenance, and provisioning (OAMP), software management, security, and high availability storage.

Wind River Accelerated Virtual Switch Software

The accelerated vSwitch within the Wind River Carrier Grade Communications Server can switch 12 million packets per second (64-byte packets) using only two processor cores within a dual-socket Intel® Xeon® processor platform running at 2.9 GHz. This represents a real-world NFV configuration, rather than a simplified configuration where traffic runs only from the NIC to the vSwitch and back to the NIC (bypassing the VM so that no useful work is performed). The performance of the vSwitch is fully deterministic and scales linearly with the number of processor cores allocated to run the function, providing the scalability required for NFV deployments that must adjust capacity to accommodate changing traffic volume.

Wind River Carrier Grade Profile for Wind River Linux

Carrier Grade Profile for Wind River Linux is the first product to meet the registration requirements of the Linux Foundation's Carrier Grade Linux 5.0 specification built for a Yocto Project-compatible product. This turnkey solution provides essential capabilities for all industries, enabling the next generation of embedded Linux designs that require secure, standards-based, and reliable solutions. Wind River Linux supports real-time capabilities based on the Linux kernel's PREEMPT features, including a special subset to comply with the CGL 4.0 specification.

High-Performance Intel Processors

Engineers planning future products, developing applications or migrating existing software will benefit from a wide range of Intel processors, technologies, and tools. Intel processors are supported by an extensive ecosystem of development tool vendors, as well as Intel tools, that enable programmers to more easily write fast, efficient, reusable code.

Radisys' T-Series Platforms for Cloud-RAN NFV

For operators requiring telco-grade reliability and performance for their Intel processor resources, Radisys T-Series are commercial off-the-shelf (COTS), open standards-based solutions that leverage merchant silicon, open-source software, and a broad range of Intel Xeon processor options. Radisys T-Series carrier-grade solutions (Figure 7) deliver high performance and five-nines reliability essential to the telecom industry.

For the hosting of virtualized network functions, Radisys T-Series platforms can be pre-configured with the latest Intel silicon processor blades.

T40 Ultra: For those applications that require the utmost in high density performance, the T40 is the ideal choice. With over one terabit of switching capacity across an ATCA chassis and the ability to deliver over 288 Intel cores, the T40 Ultra is the utmost in telecom-grade performance and is the ideal choice for NFV applications.

T40 Pro: Designed for mid-density node deployments, T40 Pro is optimized for performance per watt per space and can handle demanding Cloud RAN virtualization requirements. T40 Pro sports a 40G backplane and up to four payload slots within an ATCA form factor, allowing a broad range of network processor and compute resource blade options.

T40 Compact: The T40 Compact is a perfect network appliance, based on Intel Xeon processors, for lower-density Cloud RAN deployments

Radisys' Trillium L2 and L3 Protocol Stacks and Integrated eNodeB Solution

Radisys' field-proven LTE eNodeB software product TOTALeNodeB solution can be used to build an NFV-based cloud solution. Radisys TOTALeNodeB can natively support any architecture an operator chooses and provides the following key features:

- **Software-Only Offering:** All L2 and L3 protocol stacks, as outlined in Table 1, are included as well as RRM, OAM, and SON functionality. The solution has been ported, verified, and deployed in residential and outdoor LTE locations.
- **Platform Independent Portable Solution:** Radisys software is designed to be portable across all available board support packages (BSPs) and operating systems. Radisys LTE solution works on ARM, MIPs, PowerPC, XLR, TI DSP, Qualcomm DSP architectures with different flavors of Linux and bare metal operating environments.
- **PHY Independent:** The TOTALeNodeB solution works with any standard PHY implementation and has been integrated and proven with Intel, Broadcom, and Qualcomm PHYs.
- **Flexible Interface Definition:** Radisys software components, including protocol stacks, RRM, SON, and OAM, interface with each other in a variety of ways:



Figure 7. Radisys T-Series Platforms for Cloud RAN

- Synchronous or asynchronous mode
- Tightly-coupled function calls or loosely coupled inter-processor communications (IPC)
- Across multiple cores on one processor or multiple processors

C-RAN is Up and Coming

Exploding smart phone usage is pressuring network operators to add capacity at a time when the cost of building, operating, and upgrading the radio access network (RAN) is becoming more expensive. A new RAN architecture, Cloud-RAN (C-RAN), is providing the potential to reduce energy and TCO costs, improve spectral and resource efficiency, and facilitate the deployment of services at the edge. Still, developers of C-RAN solutions must decide how much L1 and L2 functionality, along with L3, can be centralized in the C-RAN. Regardless of the architectural approach, Cloud RAN developers need a platform that can deliver deterministic performance for virtualized workloads. The combined technology, experience, and professional services available from Radisys, Wind River, and Intel can provide the foundation for NFV architects to develop and deploy a Cloud RAN, delivering operational benefits for mobile operators.

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WIND RIVER



About the Intel® Internet of Things Solutions Alliance

From modular components to market-ready systems, Intel and the 250+ global member companies of the Intel® Internet of Things Solutions Alliance provide scalable, interoperable solutions that accelerate deployment of intelligent devices and end-to-end analytics. Close collaboration with Intel and each other enables Alliance members to innovate with the latest technologies, helping developers deliver first-in-market solutions.

The Radisys logo, consisting of the word "radisys" in a lowercase, sans-serif font, with a registered trademark symbol (®) to the right. The logo is set against a dark red rectangular background.

Corporate Headquarters

5435 NE Dawson Creek Drive
Hillsboro, OR 97124 USA
503-615-1100 | Fax 503-615-1121
Toll-Free: 800-950-0044
www.radisys.com | info@radisys.com

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