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Packet fronthaul – design choices towards versatile RAN deployments

Introduction

Several fundamental changes in the radio access network (RAN) architecture were introduced in the evolution from 4G to 5G. The radio capacity increase in 5G by utilizing new spectrum and beamforming radios, paired with the desire for more deployment flexibility to account for the variety of novel use cases, led to the introduction of new splits in the RAN protocol stack as depicted in Figure 1, [1]: The lower layer split (LLS), also known as fronthaul, and the higher layer split (HLS).

The lower layer split, between radio unit and baseband unit, was in 4G based on the common public radio interface (CPRI) in the fronthaul transport segment, [2]. In 5G, to provide better rate efficiency and node scalability, more baseband functionality was moved into the radio and the new Ethernet-based eCPRI interface was introduced, [3].

The rate efficiency and scalability are due to the fact that eCPRI carries layer data between the radio and 5G RAN compute nodes, whereas CPRI transports time-domain carrier samples per antenna. This holds true for massive MIMO advanced antenna system (AAS) radios as well as more capable non-precoding radios and supports both 4G and 5G.

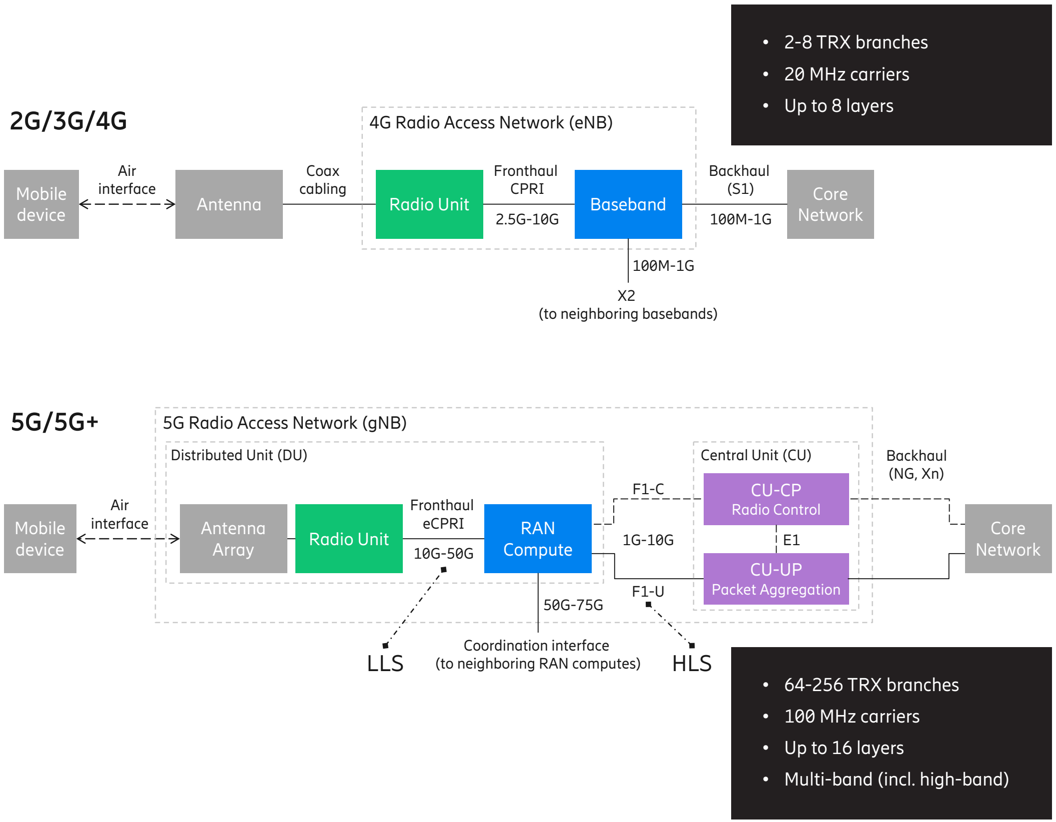

Figure 1: RAN and interface evolution in 5G

Another notable change is the use of packet technology in eCPRI instead of time-division multiplexing (TDM) in CPRI. By utilizing an Ethernet/IP network in fronthaul instead of point-to-point (p2p) TDM links, the mobile network can provide superior performance utilizing legacy and new spectrum while making optimal use of the underlying network infrastructure and RAN baseband resources. A packet network allows for planning for average utilization rather than peak dimensioning due to statistical multiplexing gains.

eCPRI facilitates for new deployment models such as centralized RANs[1] (CRAN) that complement the distributed RAN (DRAN) model commonly deployed today. RAN coordination and higher baseband utilization are better scalable with RAN compute nodes deployed in centralized hub sites. eCPRI in DRANs improves on-site networking efficiency due to the reduction of capacity requirements on the fronthaul network as well as link trunking and port expansion capabilities in Ethernet/IP switching and routing gear. The Ethernet/IP ecosystems offer well-proven and standardized tools for easing operations, administration, and maintenance (OAM) processes and to improve network resiliency, reliably, and availability.

This paves a way towards joint automated RAN/fronthaul OAM, lowering total cost of ownership.

This paper discusses the necessary evolution of the fronthaul interface to comply with the increased requirements in 5G and beyond 5G networks, and explains the design rationales behind the new eCPRI protocol, functional splits and the packet switch fabric architecture. It is shown by technical argument that the design of eCPRI/LLS is highly resource efficient and provides the flexibility to mix and match different deployment scenarios, functional splits, and potentially other services on the same packet network.

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[1] A novel higher-layer split (HLS) was specified in 3GPP rel-16 [1], allows for centralization/cloudification (NFV), control-plane/user-plane disaggregation (SDN), and the support for integrated access and backhaul (IAB) deployments as discussed in detail in [9]. HLS introduces an F1 interface between the distributed unit (DU) and centralized unit (CU).

Challenges and opportunities in fronthaul networking

With the introduction of high-rate massive MIMO radios, new 5G spectrum, and support for CRANs complementing DRANs with full performance, a (r)evolutionary step in redesigning fronthaul transport was needed to meet the challenges that Communication Service Providers (CSP) face in their deployments.

(1) Fronthaul CPRI rate explosion with massive MIMO radios: One of the main difficulties in deploying 5G with CPRI is its underlying functional split between radio and baseband. The usage of CPRI for AAS radios drives the fronthaul capacity requirements higher than 100 Gbps, which is unpractical to implement for point to point fiber links and a massive challenge for fronthaul networks.

As CPRI multiplexes baseband antenna carrier streams into TDM frames with constant bitrate, the required fronthaul capacity increases proportionally with the higher number of antenna elements in AAS radios and increased NR carrier bandwidth. This translates to many fibers or wavelengths and/or expensive photonic components in a high-capacity CPRI-capable WDM[2] optical system between RUs and baseband as shown in Figure 2 in comparison to Figure 3.

- Main deployment scenario today
- RF-PHY lower-layer split
- Time-domain multiplexing in CPRI
- Hard-wired point to point CPRI fibers / radio (parallel, WDM)
- Leased line backhaul or microwave
- Fronthaul peak-dimensioning
- RU daisy chaining and link multiplexing to baseband

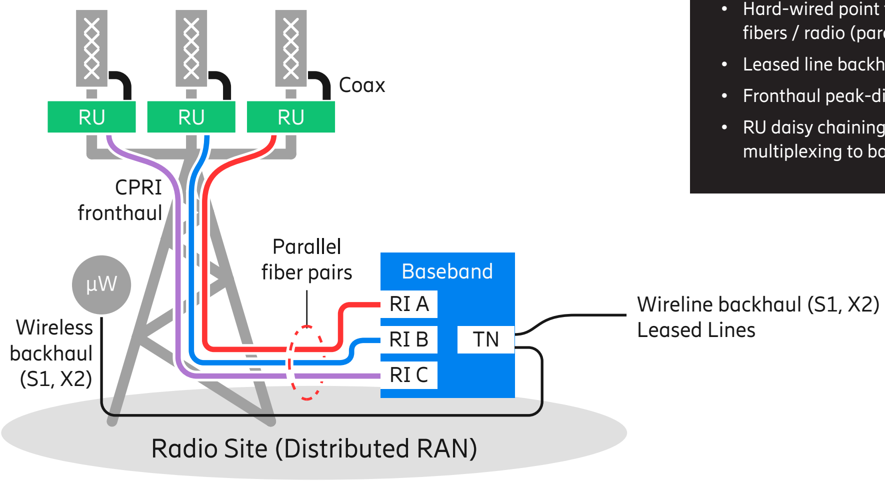

Figure 2: DRAN deployments

In short, the functional split used in CPRI is causing a large increase in bitrate with the large number of antenna elements in 5G AAS radios and therefore a different lower-layer split is needed. Also, running CPRI on individual p2p links instead of a packet network requires peak link dimensioning instead of gaining from statistical multiplexing typical for packet networks.

(2) Coordination features for best system performance: Inter-node carrier aggregation, coordinated multi-point transmission, spectrum sharing etc. are essential tools for best-in-class network performance. For 5G DRAN deployments, full coordination support between sites requires high-capacity backhaul links (expensive leased-lines or high-rate microwave links) and inter-site mesh networking for coordination, see Figure 3 and [4].

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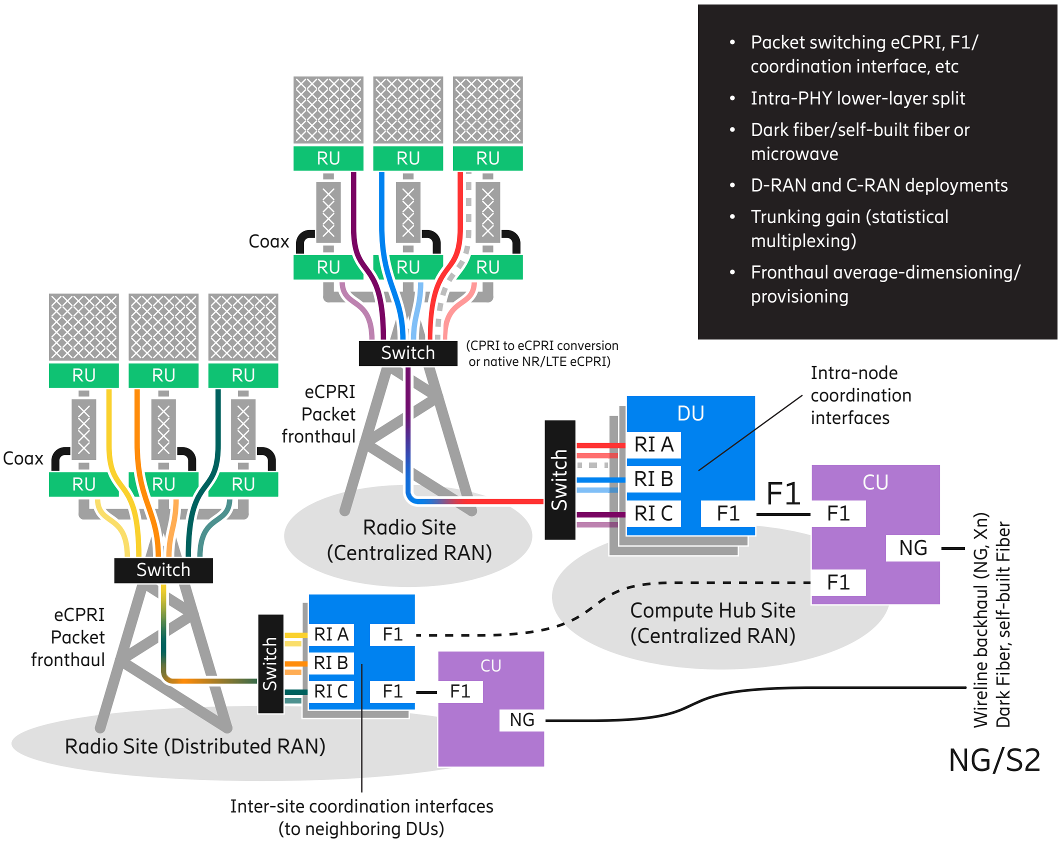
[2] In wavelength division multiplexing (WDM) systems, parallel data transmission is achieved by multiplexing different laser colours on the same fiber.

In networks with a lot of inter-site coordination, it is easier to cable between RAN compute nodes in a CRAN hub connected to the sites over a fronthaul network, than it is to build an inter-site mesh network necessary for inter-site coordination streams in DRANs. On the other hand, a CRAN system requires fiber infrastructure for the fronthaul network – either an investment in self-owned fiber or dark-fiber rental or the reuse of existing fixed fiber infrastructure.



- Packet switching eCPRI, F1/coordination interface, etc
- Intra-PHY lower-layer split
- Dark fiber/self-built fiber or microwave
- D-RAN and C-RAN deployments
- Trunking gain (statistical multiplexing)
- Fronthaul average-dimensioning/provisioning

Figure 3: 5G NR deployment scenarios (DRAN, CRAN)

(3) 5G spectrum utilization by site densification: For efficient use of new 5G mid- and high-band spectrum, multiple radio access technologies and band-combinations need to interwork together on a potentially denser site grid than what we had in 4G. In some markets, the macro-site density is not sufficient to deploy new 5G mid-band spectrum (FR1 sub 6 GHz, FR3 7-24 GHz). In other markets the grid would be dense enough for mid-band systems, but spectrum availability is limited. There, new mmW spectrum (FR2 24-52 GHz) is deployed leading to establishments of new sites in dense-urban scenarios or where fixed-wireless access (FWA) is deployed to replace fixed lines with fixed mobile broadband, see [5].

With more sites to manage and more equipment variation on site, changes in the site configuration such as adding/removing or retrofitting radios and providing network resiliency is easier done with eCPRI on a packet network using switching on frame headers (f.ex. 802.1Q VLANs) rather than CPRI's p2p links over individual fibers or optical wavelengths. The current p2p relation between radio and baseband is too rigid in terms of deployment, upgrade, and in providing network resiliency and availability.

(4) vRANs on general processing infrastructure: Operators require more efficient use of transport infrastructure while asking for more variety in functional disaggregation, the support for cloud-native network building practices such as virtualized RAN[3], and the adoption of new use-cases with varying performance requirements. Moreover, there is clear industry push towards the use of general-purpose processing and networking equipment (commodity of the shelf - COTS) and more standardized interface protocols in the mobile network. The choice of Ethernet in eCPRI makes the use of COTS possible and simplifies when building a cloud-native vRAN.

Meeting those challenges requires more flexibility in 5G deployment scenarios by mixing and matching different radio technologies, band-combinations, coordination features, and RAN splits on the same network (fronthaul, backhaul, and coordination) and explains the trend towards more centralized RAN deployments (CRAN) complementing DRAN scenarios and the use of packet transport instead of TDM-based CPRI. A switched infrastructure natively supports flexible RAN topologies and re-configuration dynamicity. A packet fronthaul solution solving the above pain points is fit for purpose in 5G and offers a great baseline for future improvements towards 6G.

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[3] In a virtualized RAN, containerized network functions that comprise the functionality of a gNB are executed on general purpose processing units like CPUs/GPUs in servers rather than special purpose signal processing ASICs.

Packet fronthaul architecture and protocols

Packet fronthaul addresses the pain-points in scalability and flexibility – the new protocol suite comprising eCPRI and LLS requires fewer fibers. It also enables CRANs effectively using new spectrum in denser site grids as it allows for statistical multiplexing of packet RAN traffic, easier OAM, and more efficient use of baseband/RAN compute resources.

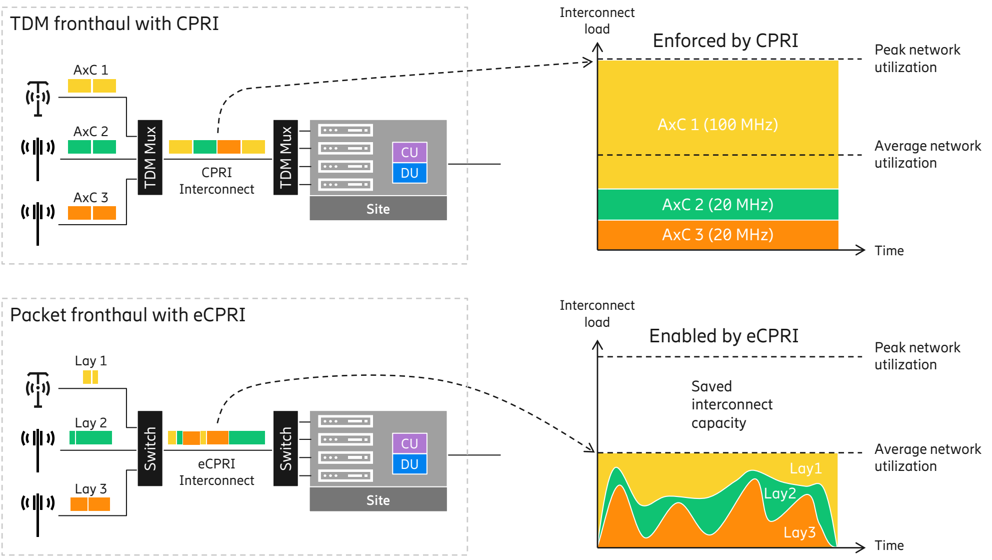
It is shown by technical argument that the design of eCPRI/LLS provides the flexibility to mix and match different deployment scenarios (CRAN, DRAN), functional splits (fronthaul LLS, backhaul HLS), and other mobile traffic on the same packet network.

In more detail, the design rationales, functionality, and benefits of technology components comprising packet fronthaul are described in the sequel.

eCPRI protocol and functional splits

Before 5G, fronthaul was dominated by CPRI, with radio frequency (RF) processing in the radio unit, and physical layer processing (PHY) in the baseband. Time-domain "IQ" samples are sent per carrier and antenna stream using constant-bitrate TDM. Only a limited set of link rates are supported (0.6-24.3 Gbps), and a specification update is needed to add new link rates. Further, fronthaul bitrate over CPRI scales with total antenna bandwidth (carrier bandwidth × number of antenna streams), which is acceptable for classic macro base stations. However, with the wider bandwidths and massive MIMO antennas in 5G NR, CPRI fronthaul bitrate, and the required number of optical links (physical fibers, or wavelengths), explode.

Different transmission characteristics of CPRI and eCPRI



In CPRI, antenna carriers (AxCs) are represented by constant bit-rate time-domain data streams for each antenna and carrier. An AxC occupies the same fixed resources in a TDM frame regardless if there is actual user-data on the carrier or not. The CPRI link can be filled up with AxCs until the CPRI line rate is reached. TDM multiplexers allow to multiplex lower-rate CPRI links into higher speed CPRI interconnection links to reduce fiber count. In eCPRI with suitable lower layer split, each data stream represents a user layer in frequency domain. The eCPRI bitrate reflects the time-varying user data; less user data means shorter or fewer packets. When aggregating eCPRI links to multiple radios, peak rate of the aggregated link becomes lower than the sum of individual peak rates since it is unlikely that all radios have simultaneous peaks. This is statistical multiplexing, allowing dimensioning based on average network utilization (with some margin) rather than on peak load, relaxing transport requirements and making the most out of baseband resources.

The new packet-based fronthaul interface, eCPRI, was introduced in 2017 to solve the 5G fronthaul bitrate issue — the aim was a ten-fold reduction of fronthaul bitrate, compared with classic CPRI, mainly by supporting, and utilizing, more efficient lower-layer splits of the base station. The eCPRI is based on packet transport and only handles user data, real-time control and certain specific eCPRI services. Existing standards are used for other functions, for example, sync is handled using IEEE-1588 Precision Time Protocol (PTP) and Synchronous Ethernet (SyncE). Any link rate supported by the underlying packet transport (Ethernet/IP) is allowed. Further, eCPRI enables statistical multiplexing gains in the packet transport, since a properly chosen intra-PHY split can support variable bitrate based on user traffic load.

The eCPRI supports several different splits with their pros and cons, for example:

- between radio functions and physical layer processing (RF-PHY) like in CPRI. Using such split in eCPRI would retain most of the disadvantages of CPRI, for example, constant bitrate, scaling with number of antennas.
- inside physical layer processing (intra-PHY), with multiple variants of the split point, which is the main focus of eCPRI. This is where most of the fronthaul bitrate reduction is realized, while still enabling advanced coordination and avoiding too much processing in the radio.

Changing split does not mean additional processing in the base station, but rather moving functionality from one node to another. Figure 4 shows that the new LLS with eCPRI means that the lower part of PHY functions (e.g. 4G/5G OFDM and cyclic prefix functions, as well as precoding/beamforming for massive MIMO radios) are moved out of the baseband/RAN (BB/RAN) compute node. New radios with native eCPRI will have this lower PHY functions integrated and can communicate directly with BB/RAN compute. Existing CPRI radios with RF-PHY split can be supported via a radio gateway, converting both the LLS, and the fronthaul interface. For simplicity, higher layer processing in the base station (e.g. in a CU) is not shown in Figure 4.

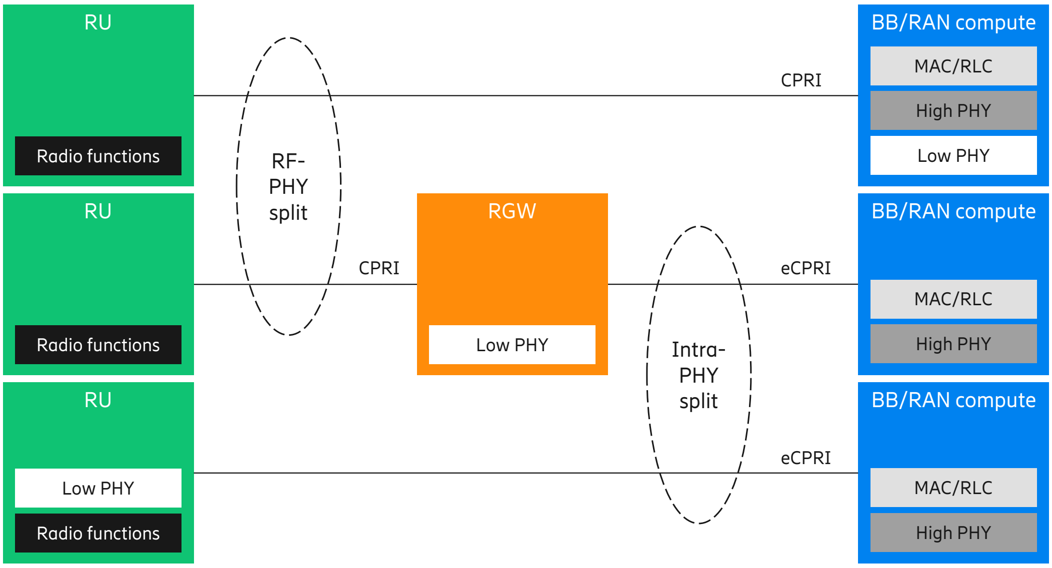


Figure 4: Illustration of new LLS, going from RF-PHY split with CPRI to an optimized intra-PHY split with eCPRI. A radio gateway (RGW) is used to handle CPRI-based RUs.

Selecting a split involves multiple trade-offs and a single split is not optimal for all applications. The RF-PHY split used in CPRI always runs at peak bitrate but can transport anything from 2G to 5G, while intra-PHY eCPRI splits are made for 4G, 5G, and beyond. Moving functionality to the RU with an intra-PHY split makes the RU more complex, but also significantly relaxes fronthaul capacity requirements. An AAS radio supporting massive MIMO can benefit from a slightly different split than a classic macro or an indoor radio. For example, if precoding/ beamforming is performed in the radio unit instead of in baseband, then fronthaul bitrate scales with the number of user layers instead of the number of antennas (like classic macro).

As explained, eCPRI was introduced to mitigate the 5G fronthaul bitrate explosion. Table 1 shows an example with 30 times higher CPRI bitrate from 4G to 5G, although peak cell-throughput only improves 11 times (5× BW, 2× num layers, 1.1× spectral utilization). CPRI compression can help, reducing fronthaul bitrate to 1/3rd, but an optimized LLS with eCPRI reduces fronthaul bitrate further, down to ~1/12th of the classic CPRI rate. Thus, with optimized split and eCPRI, 5G in the example only needs 2.5× higher fronthaul bitrate than for 4G (25 vs 10 Gbps). The key is a split where fronthaul bitrate scales with user layers.

	Carrier BW (MHz)	#Antennas/ #layers	Classic CPRI (Gbps)	Compressed CPRI (Gbps)	Optimized split, eCPRI (Gbps)
4G LTE	20	8/8	10		
5G NR	100	64/16	**300**	100	**25**

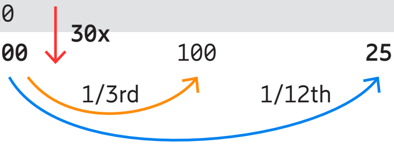


Table 1: Fronthaul data rate explosion example (approximate bitrates) when going from 4G to 5G.

CPRI is still the choice for legacy (2G/3G) support. For 4G/5G technologies and beyond, the novel LLS and eCPRI together reduce bitrate requirements on the fronthaul for classic radios, prevent the rate explosion for massive MIMO, and enables statistical multiplexing gains in packet fronthaul. Fronthaul bitrate reduction is not only an advantage for CRAN and AAS. For DRAN with classic radios, it can enable more efficient deployment and reduced cost for e.g. optical modules.

eCPRI in DRAN networks

The majority of today´s deployments are DRANs as exemplified in Figure 2 typically using wireless microwave links or leased lines (packet VPN service) for S1/NG and X2 backhaul.

In rural and suburban deployments with moderate traffic growth and mainly macro sites, an upgrade of the microwave backhaul capacity to 5G is a good option requiring moderate investments. With fronthaul then deployed on the site only, the gains of eCPRI over CPRI are somewhat limited to reducing line rates due to the new LLS in eCPRI and some local statistical aggregation gains, as well as saving of physical ports on the radio and baseband hardware, see [6].

In urban and dense-urban areas with high traffic growth and a heterogenous network of macro sites and denser small cells, the cost of per-capacity-priced leased lines as well as wavelength services (white fiber) able to carry the increased 5G backhaul traffic start exceeding the cost of leasing dark fiber, see [7].

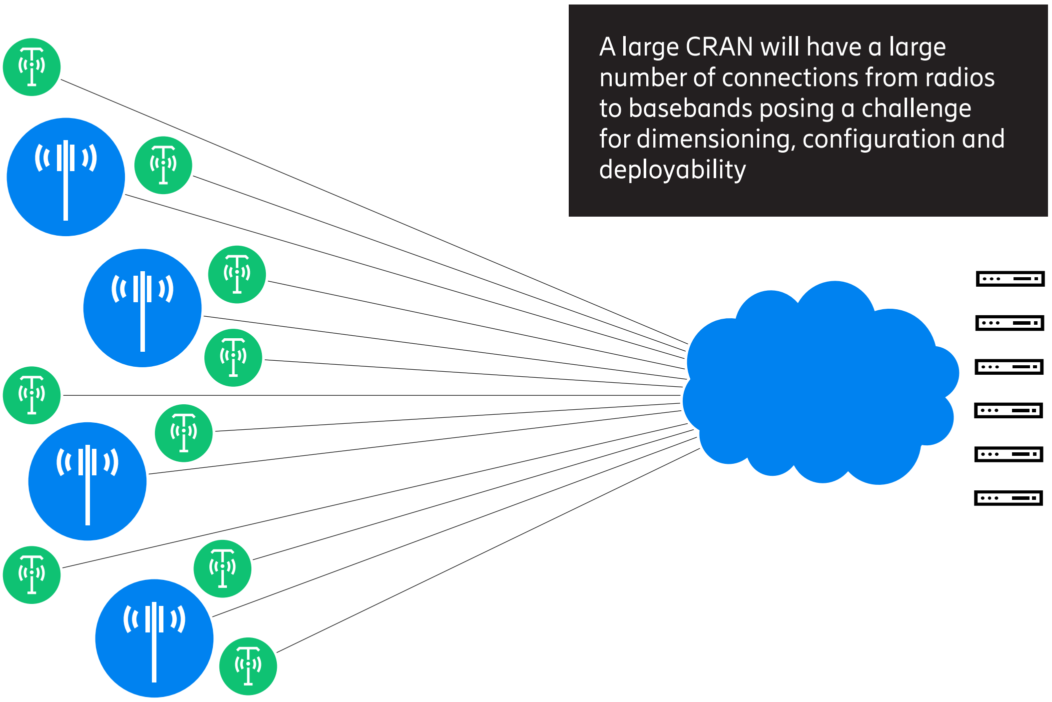
If rented dark fiber with self-built transport services is used with packet technology on top, the resulting infrastructure is then capable of carrying the demanding eCPRI streams that would otherwise not be possible with leased transport services used for backhaul. This requires a careful design of the fronthaul network providing sufficient capabilities and characteristics in terms of latency and performance.

Once the fronthaul fiber infrastructure (and centralized hub sites) is in place, CRAN deployments complementing classical DRANs become an interesting option, coming with a set of interesting new possibilities exemplified in the next chapter.

eCPRI in CRAN networks

CRANs as exemplified in Figure 5, enable key potential benefits such as antenna site simplifications, full inter-site coordination, and operational gains by centralizing processing resources into hub sites.

With the use of packet fronthaul, the relation between radios and physical ports on a baseband becomes more flexible, which together with the user data dependent characteristics of eCPRI/LLS allows a baseband to serve a larger set of radios and more efficiently use the processing capacity.



A large CRAN will have a large number of connections from radios to basebands posing a challenge for dimensioning, configuration and deployability

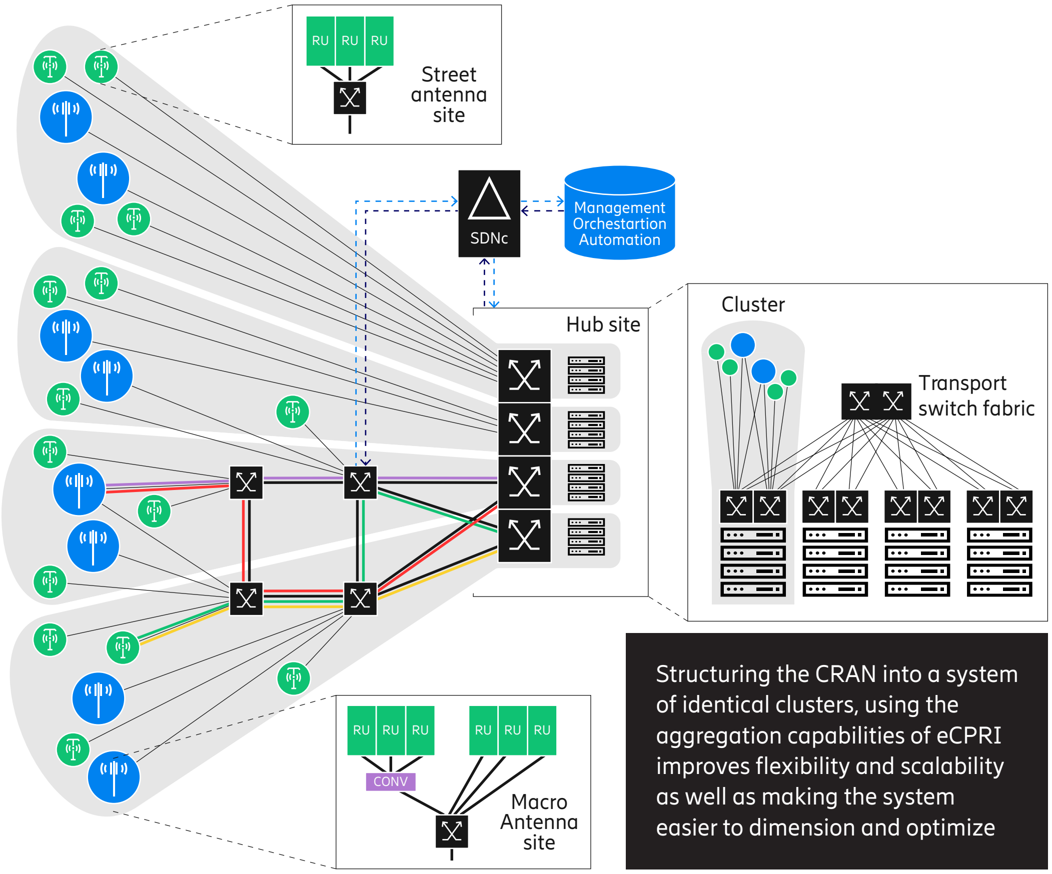
Figure 5: Centralized RAN: Radio sites connect to centralized hub site

To make best use of this property and handle the connectivity layer between RUs at antenna sites and baseband units at the hub site in a CRAN deployment, a switched FH transport infrastructure is needed to connect radios to basebands in a flexible manner. Several important characteristics need to be met, such as

- **Efficiency –** make use of the statistical aggregation possibilities in eCPRI/LLS
- **Flexibility –** allow for connectivity between all radios and all basebands
- **Scalability –** small to large CRAN deployments using the same architectural principles
- **Resiliency –** a robust network to minimize effects of failures
- **Simplicity –** a network easy to dimension and deploy
- **RAN-agnostic –** support both purpose-built and cloud-native RAN networks

The requirements outlined above can be reached by using an architecture that breaks the CRAN network down into identical clusters as depicted in Figure 6 by applying a set of principles.

- **Cluster sizing:** Groups a number of antenna sites and basebands together to form an optimally sized cluster. The configuration and size of the cluster is calculated from the required radio needs in the CRAN, taking into account both required baseband processing and geographical deployment, to give the best CRAN system performance.
- **Aggregation at the antenna sites:** Add switching functionality to the antenna sites that can aggregate eCPRI traffic according to RAN statistical dimensioning principles. This can reduce both the amount of traffic and the number of connections to the hub site, limiting the size of the needed hub-site transport network.
- **Transport network fabric:** The cluster connectivity between antenna sites and basebands is realized with a redundant and load-sharing switch pair at the hub-site, much like the leaf-switches in a data-center rack. The hub site switch pair serving a cluster is connected, with over-subscription, to a set of spine switches, creating a transport fabric. The fabric gives efficient any-to-any connectivity both within and between clusters in the system while minimizing the size of the fabric as the majority of the eCPRI traffic will stay within each cluster.
- **Serving all traffic types:** The transport fabric serves not only the eCPRI fronthaul traffic between radios and basebands but also OAM traffic to on-site equipment, packet synchronization transmission, baseband-to-baseband coordination traffic, and backhaul traffic to the local site router.



Structuring the CRAN into a system of identical clusters, using the aggregation capabilities of eCPRI improves flexibility and scalability as well as making the system easier to dimension and optimize

Figure 6: CRAN clustering example

The resulting cluster architecture has several benefits compared to the initial large CRAN. It creates smaller stand-alone units that are easier to dimension. Clusters can be replicated to build small to large scale CRANs.

The transport switch fabric makes use of the eCPRI aggregation properties yielding a transport network with fewer links and allowing for flexible any-to-any connectivity. Connectivity between clusters is reduced as they communicate via the spine switches in the hub. This results in simpler deployments with minimum cabling. The use of a resiliency principle that combines redundancy with load-sharing reduces system size and efficiently uses physically deployed functions and connectivity.

The architecture works equally well for Cloud-RAN deployments as it follows general cloud and datacenter physical deployment principles. It complements 3PP cloud infrastructure deployments but requires integration into the orchestration system.

Packet fronthaul transport network architecture

The RAN application for eCPRI is mainly using L2 Ethernet for its connectivity with tight characteristics requirements. This can be done in a simple L2 Ethernet fabric, but when the fabric introduces additional paths it becomes complex to manage and control using L2 control protocols. This can happen when adding a link to introduce redundancy in the network and can result in dropped or bad performing cells due to violation of the eCPRI characteristic requirements.

An overlay-underlay network architecture makes it possible to separate the physical network structure from the application service needs. An IP underlay can handle networks from simple to full-mesh, using protocols that have been used and are well-understood for years, for sharing network topology and characteristic information. The eCPRI L2 Ethernet traffic is handled as a virtual overlay Ethernet service with strict service requirements operating over the underlay network fabric. This can also be combined with additional virtual overlay Ethernet or IP services with different characteristics. These services can be anything from point-to-point to multipoint-to-multipoint depending on the application needs.

An overlay-underlay networking structure further improves ease of deployment and connection flexibility by being able to establish software-defined overlays with optional traffic engineered paths on the underlaying transport switch fabric as shown in Figure 6. A distributed IP based control protocol on the infrastructure makes the underlay self-contained and gives fast response to failures. Extensions in the routing protocol makes it possible to distribute the MPLS forwarding information including traffic engineering with ISIS/OSPF based Segment Routing (SR-MPLS). This also removes the need for multiple control planes, but it still uses IP and MPLS in the forwarding plane. There are also proposals to remove the MPLS forwarding plane and replace it with IPv6 based segment routing (SR)[4].

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[4] There are multiple variants for the IPv6 segment routing.

The overlay is the virtual network running on top of the underlay to create connectivity for the L2 EVPN and L3 IP-VPN services. The Multi-Protocol Boarder Gateway Protocol and the SDN controller are used to simplify the creation and control of the virtual networks and services. This includes control of the traffic engineering for the virtual service in the network by using the segment routing traffic engineering (SR-TE) capabilities in the underlay infrastructure.

The fronthaul network topology and the flexibility in 5G NR deployment architecture allows for distribution of functions to different sites for different services, and this drives the need to simplify deployment and operation of both RAN and its related transport. An SDN controlled fronthaul and management/orchestration with tight interaction between the two is needed to achieve cost-efficient deployment and operation.

Packet fronthaul synchronization architecture

When changing from CPRI to eCPRI in the fronthaul, time distribution between baseband and RU has moved from being carried by the CPRI frame itself to being carried by the packet-based precision time protocol (PTP). ITU-T has specified several PTP profiles with relevant properties for telecom, where eCPRI has selected the profile described in G.8275.1 for packet fronthaul, [8]. Requirements on time alignment and frequency stability in the fronthaul network remains the same compared to CPRI based solutions.

For the RAN to support full functionality, a performant synchronization solution must be available. With packet switches in the fronthaul network, special attention must be given to maintaining synchronization to or between radios, and sufficient synchronization availability. The switches can distribute sync and hold-over functionality located in the RAN nodes (baseband, radio) or outside (switches) need to mitigate sync interruptions from GNSS-derived sources. As a back-up, remote GNSS receivers with PTP distribution are an option.

Conclusions

The presented packet fronthaul framework provides an efficient, scalable, flexible, and future-proof toolbox for any 5G RAN deployment regardless of region or scenario.

Packet fronthaul is a solution that is fit for purpose for both DRAN and CRANs to unify transport. It eases initial deployment and configuration changes in DRANs and is a key building block for future CRAN deployments. CRANs are expected to complement DRANs in scenarios where it makes sense, i.e. where the gains in antenna site simplifications, coordination, and operations outweigh required investment in fronthaul infrastructure and hub sites.

The toolbox handles legacy RANs and migration paths which is best done by conversion from CPRI to eCPRI.

The selected lower layer split and the design of the eCPRI protocol ensure best radio performance and features support, make efficient use of the underlying transport resources and eases OAM operation. This system level vision paves the way towards a fully dynamic reconfigurable service-aware transport layer and potentially further evolution to an automated management solution.

The fronthaul packet solution, its architecture and protocols are well designed and ready for deployment of 5G and its evolution. eCPRI is the logical evolution of CPRI towards a new de-facto industry standard.

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Role: E2E Network Solution Engineer

Daniel Cederholm is an end-to-end network solutions developer mainly focusing on packet fronthaul technologies. Previous experience includes research within the areas of indoor solutions, performance management and broadband technologies. He holds an M.Sc. in engineering physics and a B.Sc. in business.

Name: Miguel Berg, miguel.berg@ericsson.com
Area of expertise: Lower layer split, eCPRI
Role: Principal Researcher

Miguel Berg is leading research on efficient fronthaul and lower layer splits (LLS) for 4G/5G RAN and is also involved in fronthaul and LLS for 6G. He holds a Ph.D. in wireless communication systems and is a delegate in O-RAN WG4 (Open Fronthaul) standardization. During the time at Ericsson, he has also done research targeting indoor small cells, and fixed access.

Name: Roger Stake, roger.stake@ericsson.com
Area of expertise: RBS architecture
Role: Expert Modular RBS Architecture

Roger Stake is Expert in Modular RBS Architecture focusing on RAN Compute architecture and implementation for RAN networks. He holds a Ph.D. in mechanical engineering and a B.Sc. in business administration and economics.