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RAN EVOLUTION PROJECT

BACKHAUL AND FRONTHAUL EVOLUTION

next generation mobile networks

RAN Evolution Project

Backhaul and Fronthaul Evolution

by NGMN Alliance

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Abstract: Mobile network operators (MNOs) are seeking efficient ways to increase the overall capacity coverage of their networks. NGMN took the lead in the definition of new RAN architectures and in the different options to improve the overall efficiency of the RAN evolution process. Concepts such as C-RAN, CoMP Carrier Aggregation and Multi-RAN address improved spectrum and resource utilizations for various scenarios. The discussion on RAN evolution also needs to address the surge in expected transport capacity, whether it is for the backhaul or the fronthaul. This paper discusses the different transport options and the relationship with traditional and emerging RAN topologies.

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1 INTRODUCTION

Mobile network operators (MNOs) are seeking efficient ways to increase the overall capacity coverage of their networks. NGMN took the lead in the definition of new RAN architectures and in the different options to improve the overall efficiency of the RAN evolution process. Concepts such as C-RAN, CoMP Carrier Aggregation and Multi-RAN address improved spectrum and resource utilizations for various scenarios. The discussion on RAN evolution also needs to address the surge in expected transport capacity, whether it is for the backhaul or the fronthaul.

The implied transport evolution to serve the mix of access technologies and topologies needs to serve MNOs' total cost-reduction goals while they are also obliged to increase transport capacity several fold to satisfy the new RAN requirements.

1.1 Objectives

This paper discusses the different transport options and the relationship with traditional and emerging RAN topologies. In specific, the shift from an all-macro layer to a mix of macro and small-cell architectures (a.k.a. Heterogeneous Networks – "HetNets"). In the following sections, we would like to portray the NGMN Alliance's view on the available options and best practice guidelines for MNOs to make optimal choices, taking into consideration the impact of RAN evolution on the transport layer.

Cloud RANs and Distributed Base Stations require tight integration and coordination compared with the traditional Distributed RAN (D-RAN). This, in turn, places higher capacity, extremely low latency and precise clock synchronization requirements on the transport. As a reminder, in C-RAN/Mini C-RAN architectures, there are semi-standard interfaces between the two elements of the base station. The interface between the Radio Unit (RU) and the Digital Unit (DU) is usually based on Common Public Radio Interface (CPRI). These interface names are used interchangeably with fronthaul. Though CPRI is a standard interface, it was not designed with interoperability in mind. There is an ETSI effort named *Open Radio Interface* (ORI) promoting an industry wide interoperable interface between RUs and DUs. When calculating all the aspects required to properly transport CPRI, it is easy to see what makes fronthaul costly to build and practically impossible to lease.

Fronthaul raises the bar for extreme capacity and latency requirements compared to backhaul. On the other hand, it probably lowers the need for QoS and security mechanisms in the transport.

Assuming that C-RAN, CoMP, Carrier Aggregation and HetNets bring significant economic benefits to MNOs, we need to understand if we should expect an increase in the transport cost and whether this can be offset by increased utilization of access spectrum and equipment.

1.2 Sources and structure

This paper is based on inputs from the various workgroups and projects operating within the NGMN in including RAN Evolution and Small Cells projects. In specific, the C-RAN workstream project contributed fronthaul requirements for C-RAN; the CoMP workstream contributed ideal and non-ideal backhaul requirements.

Section 2 analyzes reference architectures for comparisons between fronthaul and backhaul. Section 3 drills down into the notion of hybrid fronthaul and backhaul concurrent transport of traffic with a focus on migration. Section 4 describes relevant fronthaul solutions available. Section 5 examines options for fronthaul as a service (managed CPRI)

2 REFERENCE ARCHITECTURES AND USE CASES

This section provides a high-level qualitative comparison between the different transport options for the evolution of RAN topologies. The main drivers for this evolution are new LTE-A features, such as eICIC and CoMP, over ideal or non-ideal backhaul. Before we continue, these concepts, ideal and non-ideal backhaul, defined by the 3GPP, should be clarified. Generally speaking, ideal backhaul means less than 2.5 usecs latency and about 10 Gbps of capacity. While non-ideal is the range of 5-30 msec latency, but can be even more in the case of DSL or cable access. On the other hand, we need to weigh the (perceived) cost of more advanced access units and the total (perceived) cost of the transport segment.

2.1 Dimensions of comparison

Deployment strategy depends on multiple considerations. For the simplicity of discussion, the following items were selected for comparison:

- Topology, resiliency, capacity and latency
- Cluster size, number of RUs per DU and the inter-cluster management
- Operational benefits like power consumption, air conditioning and truck rolls
- Real estate including site acquisition, shelter and rack space
- Current and planned access spectrum portfolio

Obviously, there are many more items and there is a wide business case variation based on geography, available assets and regulations. There are a few other considerations and questions that are important to address:

- What are the implications of multi-RAN in backhaul (BH) and fronthaul (FH)? In other words, how should we handle 2G, 3G and Wi-Fi over Ethernet in parallel to CPRI for LTE as part of the migration?
- What are the benefits of reducing networking overheads when shifting from backhaul to fronthaul? A few examples are the need for encryption in some cases or the use of CSG/CSR at every site.
- How do we evaluate the benefits of features only available through ideal backhaul? (Such as dual attachment/carrier aggregation, joint processing and joint transmission, all of which come almost for free in a distributed BTS)

The next few sections would try to summarize these different dimensions and factor them into various deployment models.

2.2 Comparison dimensions explained

Current and planned access spectrum portfolio

The single most important factor in planning a mobile network is availability of access spectrum. This is usually the most expensive OPEX/CAPEX factor. The wider the channels, the more capacity the MNO can provide. Lower frequencies make it easier to provide coverage. Higher frequencies, on the other hand, make it easier to improve capacity coverage with high spectrum reuse without the need for strict coordination. MNOs start their network design from how much capacity they need to deliver in order to be competitive, taking into account the available spectrum assets today and in the future. While we have said nothing new until now, the emerging drive for spectrum reuse as presented in LTE-A, coupled with site densification, impact the design of transport networks.

LTE-A capacity benefits

The introduction of LTE-A presents new options for improving spectral efficiency. eICIC, CoMP over ideal or non-ideal backhaul and Carrier Aggregation expand access spectrum usage and reuse options. These new features deliver capacity improvements measured at the cell edge and/or as average throughput of cells.

Here are a few examples to demonstrate capacity-transport tradeoffs:

- eICIC improves average throughput and it comes with almost no requirements from the backhaul. However, it is often delivered through the implementation of IEEE 1588-2008 over backhaul which can make planning and deployment more complex.
- CoMP over non-ideal backhaul performs better in the downlink (DL), but it comes with a target of 5 msec latency one way (half of what we require generally for LTE).
- Uplink (UL) CoMP over non-ideal backhaul, on the other hand, requires mobile protocol adjustments to coexist with traditional packet based transport. It can improve cell-edge performance, but it reduces peak throughput by half, making it less appealing. The interesting part is that applying intra-site CoMP, i.e., UL CoMP between sectors of the same physical site, shows potential and might reduce the motivation for further sites densification
- Most other CoMP and Carrier Aggregation schemes require ideal backhaul to operate and deliver the better capacity coverage promise.

To conclude this section, while it is possible to improve capacity coverage significantly without fronthaul, many of the more advanced LTE-A features assume fronthaul for the time being.

Perceived cost of access units

Commercial terms and pricing are beyond the scope of an NGMN paper. These tend to be operator/vendor-specific and related to installed base and scale of contracts. Still, we would like to pose a few relevant questions to ask when selecting the most optimal access equipment as these have significant implications on the transport side.

We assume there is a substantial cost involved in providing the new feature sets. Either newer hardware is required or, perhaps, software upgrades or additional licenses. As discussed, there are plenty of access options to increase capacity coverage. For example, MNOs should consider the cost of the access equipment necessitated by each of the models. Just as an example, compare the cost of the following three scenarios:

1. Access: 3 RUs per DU and 3 DUs overall
   Transport: Backhaul to 3 eNBs
2. Access: A single DU with 3 RUs co-located, and then an additional six separate small cells
   Transport: Backhaul connection to the eNB and then six backhaul connections to the small cells
3. A single DU with 9 RUs overall, some co-located and some located remotely
   Transport: Backhaul connection to the eNB and then six fronthaul connections to the remote RUs

While these options might provide similar performance measures, for a complete evaluation, we need to factor in the cost of access equipment with the cost of the transport network. We also need to define similar performance measures. In our case, there might be similar requirements from the backhaul-to-core perspective, but in terms of Quality of Experience (QoE), average cell throughput and cell-edge performance can be more important to the user.

Perceived Cost of Transport

The correlation between cost and capacity or latency is rather trivial. Imagine relevant pricing schemes of leased transport for 100 Mbps, 1 Gbps, 2.5 Gbps respectively and then, in turn, compare it with dark-fiber lease pricing that offers unlimited capacity. Now, imagine different SLA options of 100 msec, 20 msec or 500 usec (Micro Seconds) round-trip latency time. To this practical exercise, we can add availability, optional clock accuracy and distance surcharges.

Now, imagine a transport service to provide capacity at 2.5 Gbps steps with 500 usec[1] round-trip-time not to mention CPRI-level clock accuracy. This is fronthaul.

MNOs considering large C-RAN deployments[2] require a sizable fronthaul network. Fronthaul as big as we have discussed may require solutions mentioned in the section 4 on fronthaul solutions. This means a fronthaul network needs to rely on extensive fiber assets and availability of fiber at almost every site. The fibre should be self-owned or based on leased services with the ability to deliver the stringent service level that CPRI requires in a managed fashion.

A quick note on target latency for fronthaul: Though the industry target for maximum latency in the fronthaul segment to allow support in the DU is 500usec round-trip time, most existing solutions are still implementation-specific and are designed around a 100-400usec RTT latency budget only.

Cluster size

By cluster size, we refer to the number of RUs managed by a single DU (or DU hotel). Potentially, the larger the cluster, the more benefits we gain from central spectrum management, as well as from the operational benefits of centralization. In the future, virtualization will improve the benefits derived from huge clusters making it possible to load-balance across mega cities. On the other hand, there is a diminishing return from the size of the cluster when it comes to capacity improvements based on CoMP and, more important for our discussion, the larger the cluster, the more challenging the design of the supporting transport network.

Operational benefits

The business case must take into consideration the impact of RAN design on the total cost. This analysis must include real estate, site acquisition, shelters and rack-space cost. It also must include other passive and active equipment required for the site. Operational aspects include power consumption, air conditioning, the cost of truck rolls, etc.

2.3 Comparison models

The different models in this evaluation take different approaches toward the evolution to Heterogeneous Networks. This is not an exhaustive list of all possible permutations just a representative list of four alternatives and a single reference architecture.

1 The equivalent of 50 km over dark fiber taking into account signal propagation delay in fibre
2 More on the rationale behind such a sizeable C-RAN implementation can be found in the NGMN C-RAN workstream

2.3.1 Base model for comparison

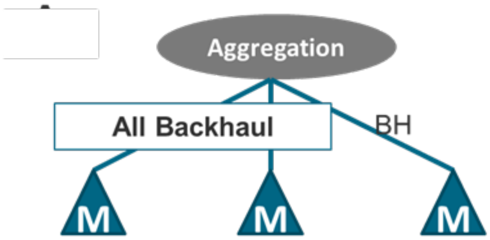


Figure 2-1: Base model for comparison

The base line for this work is a macro-only, all-backhaul topology. This is obviously the main path for RAN evolution going forward where macro cells are evolving into super macro cells hosting far more spectrum and employing techniques such as intra-site CoMP to improve spectrum reuse and overall utilization. The advancements of both the radio access and the transport products means that, in terms of form factor or power consumption, the improvement in capacity coverage comes at no additional cost.

2.3.2 Backhaul-based

Before approaching the fronthaul-based topologies, a quick review of topology migration options to HetNets. It should be noted that MNOs may, for practical reasons, implement a combination of these two approaches.

Small cells as an overlay and all-backhaul

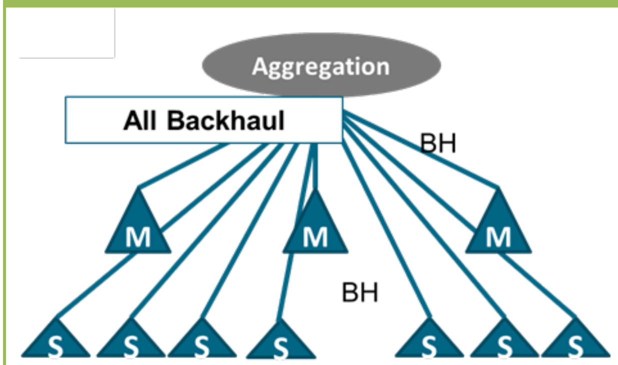


Figure 2-2: Small cells backhaul as an overlay

This concept describes a small cell overlay and an overlay of the transport network to fulfill the new location requirements. This concept assumes that interferences do not offset the additional capacity offered by the new small-cell layer. A scenario that might satisfy this assumption is the case where the small-cell layer uses a separate spectrum slice. Another relevant scenario is allocation of small cells to indoor or locations known as not-spots where interference mitigation is not critical. In these cases, there are no special requirements from the small cells or the macro layer in terms of vendor, software or technology support

Backhaul to macro and then backhaul to small cells

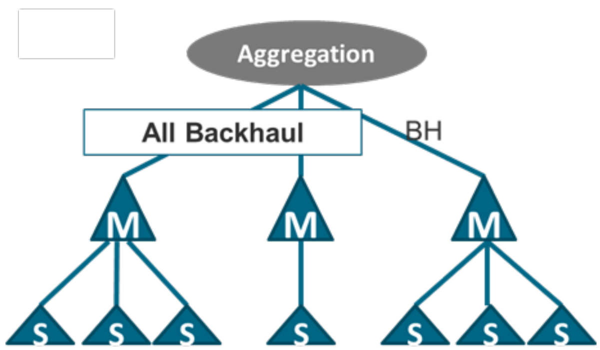


Figure 2-3: Hierarchical Backhaul

This concept describes a small-cell layer that emerges from the macro layer. The fact each small cell is connected to the macro cell covering the area allows for coordination techniques such as eICIC or CoMP over non-ideal backhaul. Though this scenario might appear similar to the small cells backhaul as an over overlay, from the logical perspective, the main difference is the physical connectivity and, more important, the upgrade path. This, in turn might imply interoperability between the small cells and the macro layer protocols for coordination to increase value.

2.3.3 *Fronthaul -based*

As discussed previously, many LTE-A features require an ideal backhaul to perform optimally. In other words, they require a fronthaul transport. Two common approaches are illustrated below:

Hybrid Architecture: Backhaul to macro and then fronthaul to small cells

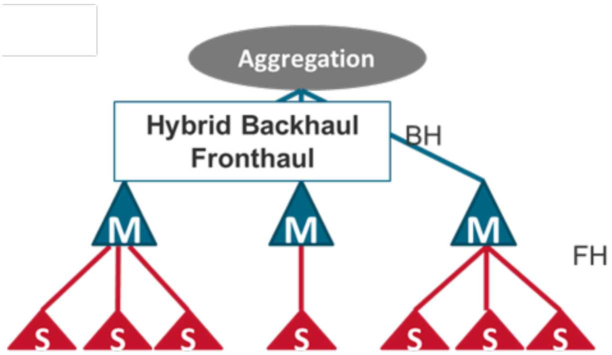


Figure 2-4: Hybrid BH/FH Architecture

This concept describes a small-cell layer that is built from RUs extending the macro layer. The fact that each small cell RU is using fronthaul to the macro cell allows for CoMP over ideal backhaul. This also means very tight coordination and interoperability. This concept promises efficiencies due to higher spectrum utilization by using larger, distributed base stations, moving away from 3 to 6 sectors per base station to a world with 6 to 12 or even more RUs connected to a single DU. But all of these need not be located physically on the same rooftop or tower. Efficiencies come from deploying the additional RUs on close-by rooftops or even on remote towers.

Fronthaul from DU Hotel to macro and small cells

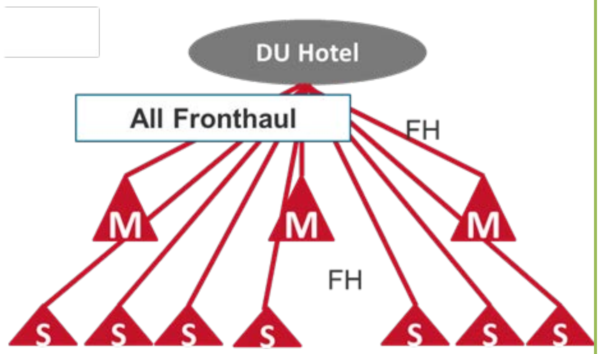
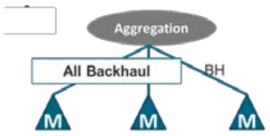
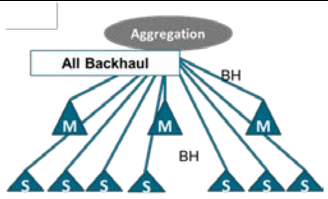
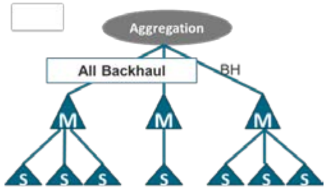
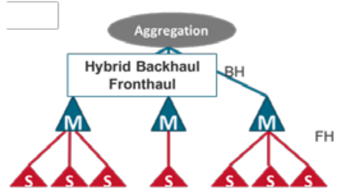
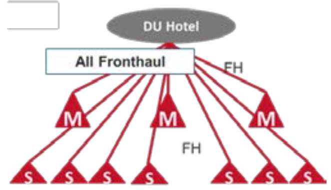


Figure 2-5: All fronthaul Architecture

This is a C-RAN concept used both for the small-cell layer and the macro-cell layer. A DU Hotel can handle hundreds of RUs and these RUs may be of any type, macro or small cells in clusters or standalone. Overall, an all-fronthaul network supporting high capacities and low latencies is required.

2.4 Comparison table

	Base model for comparison	Small cells as an overlay and all-backhaul	Backhaul to macro and then backhaul to small cells	Backhaul to macro and then fronthaul to small cells	Fronthaul from DU Hotel to macro and small cells
					
Summary	Evolutionary capacity improvement in existing sites	Evolutionary capacity at macro layer and a disruptive orthogonal small cell layer	Evolutionary capacity at macro layer and a coordinated small-cell layer extension	Evolutionary capacity at the macro layer and a tightly coordinated small-cell layer extension using fronthaul	A disruptive transport change at both macro- and small-cell layers shifting to all-fronthaul.
Pros	• Maintains the same network concept • No need for significant new site acquisition • Implies less risk	• A simple approach to add small cells • Perceived lower total cost • May utilize a parallel broadband network for the small-cell layer backhaul	• A straightforward add-on of the small-cell layer • Effective also in dense scenarios with multiple interferences • Significant capacity coverage improvement	• Effective also in dense scenarios with multiple interferes • Capacity coverage improvement in terms of cell edge and average capacity	• Perceived as the most efficient deployment scenario • Significant capacity coverage improvement • Pooling benefits as the cloud gets larger
Cons	• Effectiveness of the capacity coverage • Size of macro cells	• Dense deployment effectiveness • Low value in the installed-base assets, real estate, PoPs, etc.	• Requires interoperability to achieve dense deployment effectiveness • Special requirements from the backhaul in terms of latency and timing	• Requires tight coordination and therefore calls for fronthaul	• Requires massive transport to cater to the fronthaul requirements • Diminishing return from coordination as the Cloud gets larger.
Bottom line	Any move from this model implies increased cost and complexity	Appealing to operators with separate spectrum relevant for small cells	Most compelling for operators relying on transport-as-a-service for their backhaul	Cost effective and in line with competitive mobile operators network topology and assets	Fits well into incumbents' network topology, fibre facilities and real estate

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3 MIGRATION FROM BACKHAUL TO FRONTHAUL

This section explains further the notion of mixed backhaul-fronthaul networks in terms of the need for a dual-transport technology support to every site during the migration phase. This section complements Section 2's topology discussion with two additional dimensions:

- Serving a Multi-Radio Access Technology (RAT) environment and migration
- Addressing both the case of a single operator and the case of network sharing between operators

This is a generalized discussion on the migration process, but for the sake of simplicity, we present the single-site perspective and not within the complete HetNet.

3.1 General considerations

Todays' backhaul networks are planned to support a multi-RAT macro layer and are expected to support a new LTE-based small-cell layer. Generally speaking, the network needs to handle the capacity, latency and sync distribution requirements.

The drive for a hybrid architecture concept comes from the set of benefits of LTE/LTE-A, already achievable in relatively small clusters. LTE-A enables mobile operators with limited fiber facilities to enjoy higher RAN efficiencies with cost-efficient backhaul to a DU managing a small cluster of remotely installed RUs connected by fronthaul.

When using the baseband capability to support both macro and small cells in a given contained vicinity, the advanced functionality can be put to work with dual-attachment, carrier aggregation and advanced CoMP schemes such as Joint Transmission/Joint Scheduling (JT/JS)

While providing fronthaul for a cluster the size of a city – a.k.a. C-RAN – requires a large amount of fiber assets and relevant DU hoteling locations, small clusters mean somewhat higher performance at the backhaul segment and then reduced requirements for the last, short-range fronthaul segment. This enables the use of a wide range of fronthaul solutions – both wireline and wireless.

For each of the following cases, we will first create a common deployment scenario to be used as base line and then offer a probable migration strategy. The following notation is used in the next few sections:

- Traditional backhaul: ↔
- Fronthaul ↔
- Tx refers to transport, likely to include CWDM once parallel backhaul/fronthaul is implemented
- CSG stands for Cell Site Gateway/Router
- MRAN refers to multi-RAN base stations (sometimes referred to as Single-RAN or SRAN). Simply put, any combination of GSM, UMTS or LTE is possible
- SO stands for Single Operator; MO stands for Multi-Operator
- MORAN MO-Radio-Access Network but in the context of 3G

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The base mode for this discussion is a hierarchy where operators use traditional backhaul to the macro cell and then fronthaul to the small cell as descried in Figure 3-1. In a sense, this is a zoom-in of topology described previously.

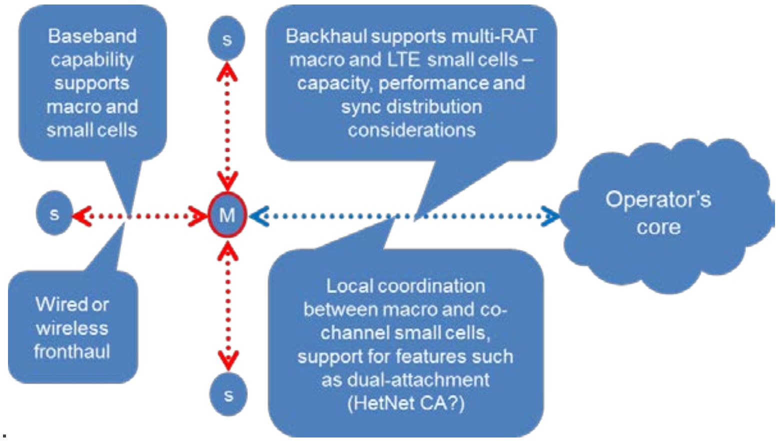
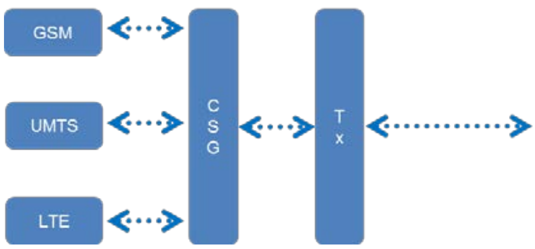


Figure 3-1: Hybrid backhaul/fronthaul architecture scenario base model

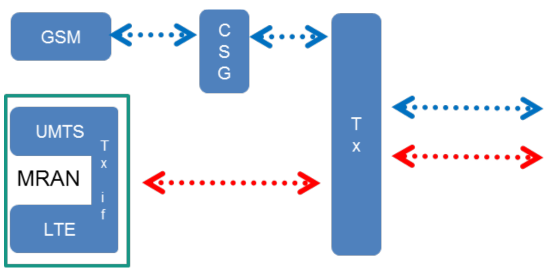
In the next few sections, we review various migration scenarios in the macro-cell backhaul segment both for single operator and for multi-operator scenarios

3.2 Requirements for a single operator

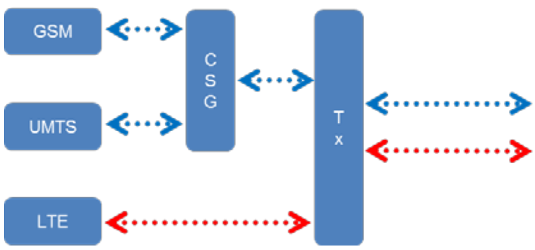
The base model for a single operator (SO) is described in Figure 3-2: Hybrid fronthaul/backhaul for a single operator (SO). The CSG functionality is denoted as a separate box to simplify the migration and to emphasize some of the benefits with some of the options. We acknowledge that in some sites, CSG functionality might be part of another element (e.g., Tx/CWDM platform) or, in some sites such as small cells, CSG functions might not exist at all. For further references on LTE deployments, please see the NGMN rew revision of the Deployment Scenarios white paper



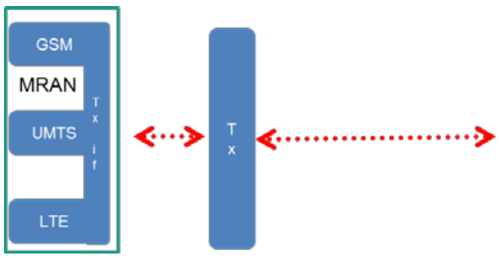
a. All backhaul (SO)



c. Hybrid Option II (SO)



b. Hybrid Option I (SO)



d. All fronthaul (SO)

Figure 3-2: Hybrid fronthaul/backhaul for a single operator (SO)

The need for a hybrid transport (in the sense of concurrent transport to a site), we should split into two options. The first is straightforward. The 2G/3G remain over the traditional backhaul with the existing topology, but for LTE/LTE-A, we implement fronthaul to enjoy all the new capabilities.

The main difference between Option I and Option II is the use of both 3G and 4G in the same base station, i.e., MRAN. The end game might be a multi-RAN environment with an all fronthaul transport as described in Figure d above.

Adding WiFi as a consideration might lead to long-term hybrid traffic requirements. Another issue that might impact the decision for a hybrid traffic scenario centers around fronthaul over Ethernet migration scenarios. The operator must also consider timelines for migration to fronthaul: Will the 2G and/or 3G network still be operational by this time?

3.3 Requirements for network sharing

The case of multiple operators (MO) is similar to the transport topology and from a high-level perspective. However, from the perspective of what the requirements are both in backhaul and fronthaul, we need to assume at least the following in the backhaul:

- Higher capacities
- Service differentiation (VLAN QoS /HQoS) and appropriate Operations and Management (O&M)
- Multiple time and security domains

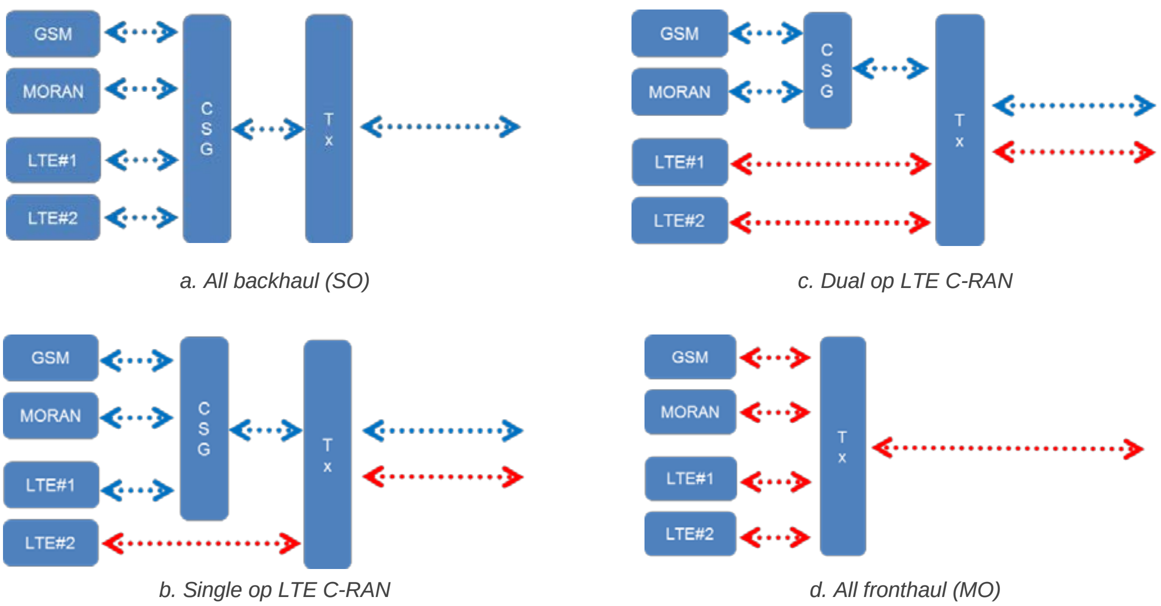


Figure 3-3: Hybrid fronthaul/backhaul in the network-sharing case (MO)

Figure 3-3 describes the migration steps in a Multi RAN macro from all backhaul to a hybrid traffic backhaul and fronthaul to all fronthaul. Even more important for the discussion are the special requirements in the fronthaul for Multi-RAN, Multi-Operator C-RAN scenarios covered by the NGMN C-RAN workstream.

3.4 Hybrid backhaul/fronthaul concurrent traffic summary

Hybrid backhaul/fronthaul based on the macro layer and its underlying small cells is an interesting architecture which appears to offer RAN capacity and/or performance benefits. The likelihood of a Multi-RAT cell site having legacy services on backhaul while migrating LTE to a C-RAN architecture as a 1st phase is probable and should, therefore, be considered. This raises the need for hybrid transport mechanisms such as CWDM, or hybrid wireless, very similar to the solutions available for the migration from TDM to all-packet. On top of the concurrent traffic requirements, a wide range of site- and infrastructure-sharing models which should be considered within the context of network migration to C-RAN.

4 RELEVANT FRONTHAUL SOLUTIONS

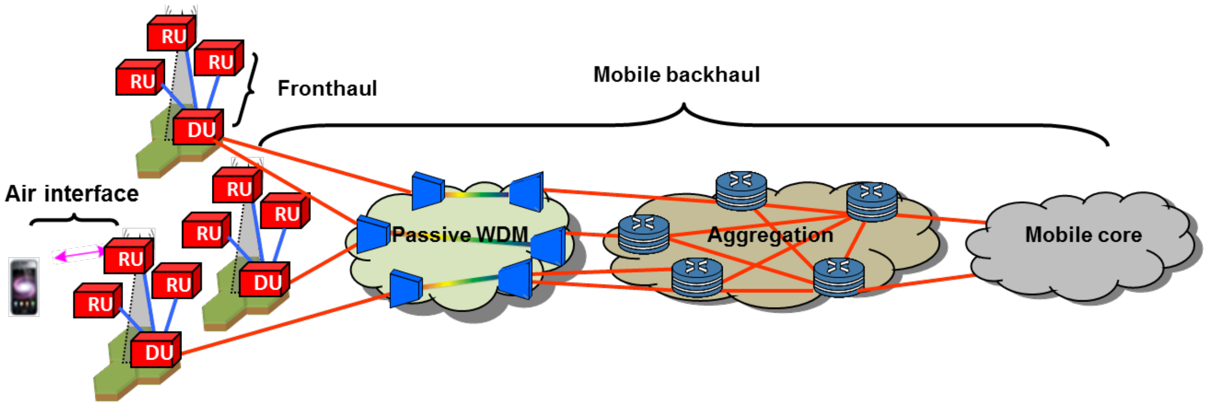


Figure 4-1: General fronthaul/backhaul architecture

Shifting from today's architecture, where baseband modules are located at antenna sites, fronthaul spans only short distances between the RU and the DU. Mobile backhaul spans the section between DU (baseband) and mobile core. Gigabit-Ethernet connection for the traffic of LTE, UMTS and GSM per 3-sector site is usually sufficient.

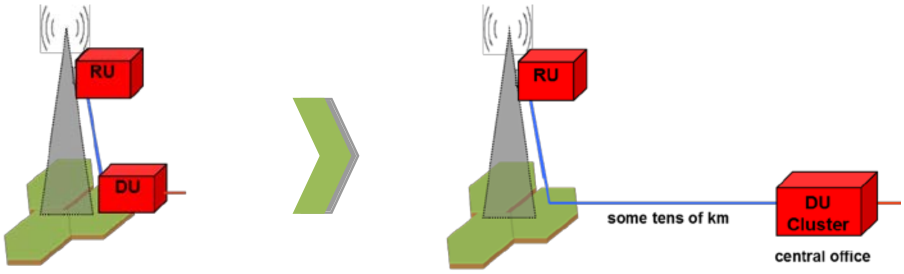


Figure 4-2: Fronthaul evolution from a local connection to a remote

Figure 4-2 describes the evolution from local connectivity of the RU and the DU to a remote setup. The question is: What are the options we may consider to allow the separation of the DU and RU sites?

The fronthaul distance is not limited by the transport technology but by the implementation of HARQ protocol in the uplink of LTE. In order to support a 50km fronthaul network in HARQ protocol, the one-way delay budget for fronthaul transmission must be at least 250µs solely considering light propagation delay. Therefore, when seeking relevant fronthaul solutions, we need to consider the following basic requirements

1. Capacity – CPRI Option 3 (2.457 Gbps as minimum) with scalability to CPRI Option 8 (10.137 Gbps)
2. Jitter – strict per CPRI specification[3]
3. Latency – sub-100usec one way, but expected to grow to 250usec
4. Scalability – support for multiple RAT technologies, C-RAN-sharing
5. Distance - need to assume 1-10km reach for most deployments, but also 20-50km for large clouds

[3] The specification does not consider the transport of a CPRI signal over a network and, therefore, doesn't partition the overall margin (delta between Rx and Tx among the local interfaces and the fronthaul network. Depending on the CPRI option, the maximum additional jitter generated by the fronthaul is in the range of nanoseconds or sub-nanoseconds.

The next few sections include a range of options that can be considered for the different fronthaul scenarios

4.1 Case 1: Dark fiber

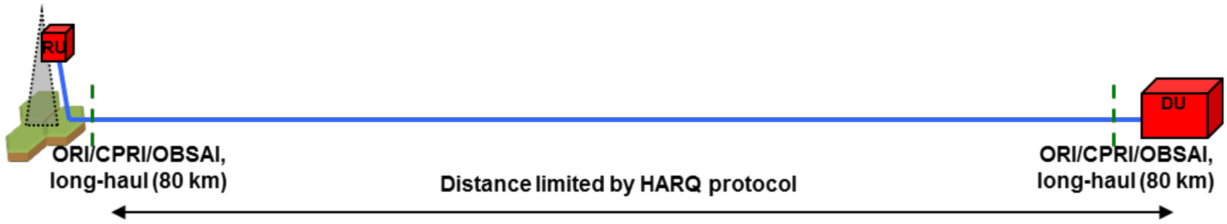


Figure 4-3: Dark fiber

Deployment over dark fiber is a straightforward option; however, it requires high CAPEX. Standard optical pluggables (SFP) allow for transmission up to 80km or more without amplifiers, which is actually not necessary for fronthaul due to its delay limitations.

Summary

The most common option for fronthaul

Pros	Cons
• Meets current and future requirements • Simple to deploy	• Cost as a service • Availability at every location

4.2 Case 2: Passive WDM (pWDM)

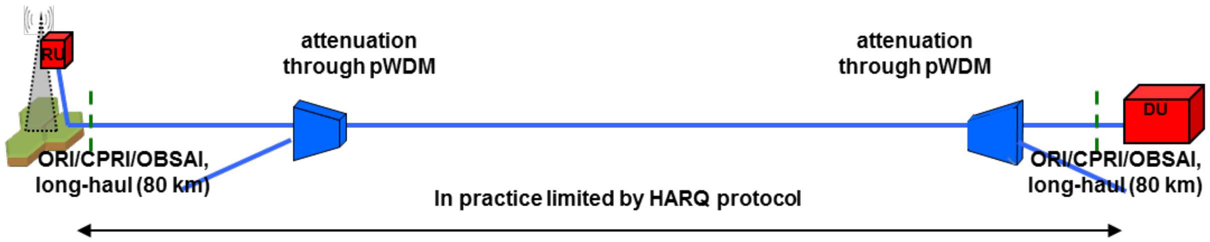


Figure 4-4: pWDM

Standard CWDM or DWDM pluggables are able to bridge up to 80km, and extended CWDM pluggables - up to 120km. These distances, however, do not include the additional attenuation of pWDM filters or other equipment and are based on typical power budget for pluggables. The latency of the system is caused by the light-propagation delay only—passive WDM filters introduce no additional delay. pWDM allows for transmission rates up to 100Gbps (all digital data rates including CPRI). Increasing data rates is possible by adjusting interfaces, not infrastructure. The multiplexing factor/splitting ratio is up to 80 wavelengths.

Summary

Similar to the dark fibre option but with better reuse of facilities

Pros	Cons
• Meets current and future requirements • Relatively simple to deploy • Reduces the number of fibre pairs required for macro base stations deployment	• More expensive compared to dark fibre • Not manageable as a network and still costly as a service • Complex operations

4.3 Case 3: Injection-locked SFP with WDM (WDM PON)

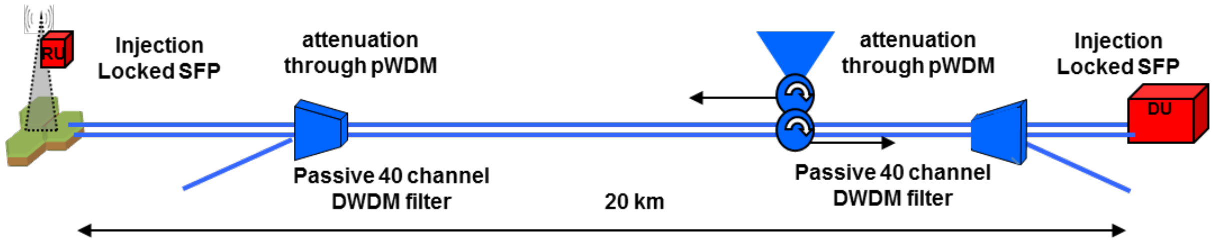


Figure 4-5: Injection-locked SFP with WDM (WDM PON)

A pWDM solution as described in Section 5.2 based on DWDM optical interfaces can run up to 40/80 wavelengths on one fiber pair. The costs of such a solution are driven by the prices of the DWDM optical interfaces. A very economical alternative to traditional DWDM-based 40 wavelength infrastructure is WDM PON with injection-locked SFPs.

In order to make the injection-locked SFP operate as expected, a seed light is required. The seeder adds this seed light to the system. The seeder sends out a broadband light source from the central office out towards each WDM-PON access node that contains a colorless SFP and that is connected to the access network filter structure.

When receiving the seed light from the central office, each SFP tunes into that specific frequency. The SFP tunes to the specific wavelength that is defined by the physical fiber/filter infrastructure. For example, an SFP located at an endpoint that is connected to wavelength number 23 in the fiber plant will automatically tune to wavelength 23.

This automatism has several advantages:

- No wavelength planning is needed; there is one SFP for all end points
- No configuration is needed in endpoints
- Easy inventory management and product forecast
- Optimizes supply-chain management
- Minimizes installation and commissioning errors
- Parallel usage of standard SFPs, XFPs and injection locked SFPs
- Distance - 20km
- Latency - light speed, no further delays
- Transmission rates for injection-locked technology 1Gbps, CPRI
- Transmission rates for non-injection locked technology up to 100Gbps (all digital data rates incl. CPRI)
- MUX factor/splitting ratio - 40 wavelength

Summary

Similar to the dark fibre option but with better reuse of facilities

Pros	Cons
• Meets current requirements • Simple to deploy and operate • Reduces the number of fibre pairs required for macro base station deployment	• More expensive compared to dark fibre or pWDM yet limited in capacity • Not manageable as a network and still costly as a service • Availability at every location

4.4 Case 4: Active transparent WDM

An active or classical WDM system may be used in the access network for bridging longer distances, but it is not worthwhile for fronthauling in case of many network operators since the fronthaul length is limited by HARQ. Also, keep in mind that fronthaul is very sensitive to introduced delay and jitter.

4.5 Case 5: Microwave

Figure 4-6: Microwave

Microwave or millimeter radio solutions perform as fiber replacements in a wide range of applications, but mainly used for backhaul where fiber is not available, too costly or just to time-consuming to deploy. The bit rate of the fronthaul interface is higher than the corresponding backhaul interface and, therefore, requires more spectrum from the radio link. Though propagation in the air is faster than in fiber, due to required processing and modulation necessary in radio-based fronthaul, typical distance is capped.. As wide channels required for the capacity are available, mainly in relatively high licensed spectrum such as 18-42 GHz or 70-80 GHz (E-Band), practical distances due to atmospheric attenuation, range from a few hundred meters up to 7 kilometers.

In terms of capacity, radio-based solutions accommodate symmetrical 1.25Gbps to 2.5Gbps CPRI rates and in the near future even higher CPRI options. Additional CPRI compression can reduce the capacity required by a factor of up to three and improve the scalability and usability. Generally speaking, the main fronthaul application for microwave is the distributed BTS concept, increasing the number of RUs per DU from 3-4 in a single site to 6-12 spread over few low footprint sites.

Summary

Accommodates small-scale fronthaul scenarios in both urban and rural environments to complement fibre

Pros	Cons
• Bridges fibre deployment gaps cost-effectively • Instant and familiar in similar ways to backhaul applications	• Requires wide channels • Limited deployment scenarios • Sensitivity to latency and interoperability

4.6 Case 6: Ethernet

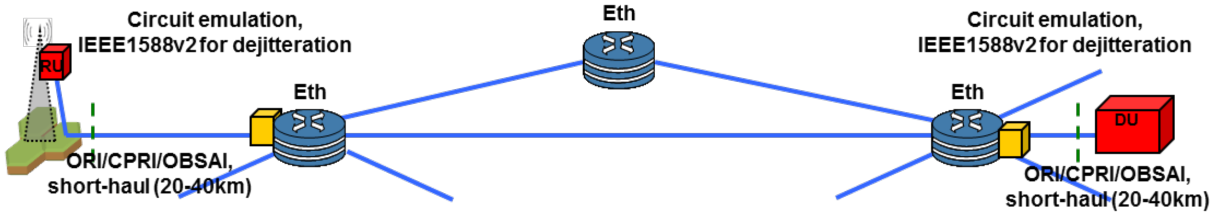


Figure 4-7: Ethernet transport

Ethernet for transport requires addressing the need for circuit emulation of ORI/CPRI signal over Ethernet and its inherent delay and jittering. It is difficult to meet the strict jitter requirement of CPRI. The inherent Ethernet delay reduces the maximum practical fiber length between RU and DU. Moreover, fiber needs to be kept in the same track to avoid delay asymmetry for upstream and downstream, in order to allow calculation of Time of Day needed for synchronization. More about the Ethernet option in the next section

Summary

Provides a common network layer ready for various leased transport services

Pros	Cons
• Provides statistical multiplex gain for BH • Possible use of Ethernet for BH and FH	• Special circuit emulation for CPRI • Circuit emulation increases the used Ethernet bandwidth • Introduces limitations

4.7 Case 7: OTN

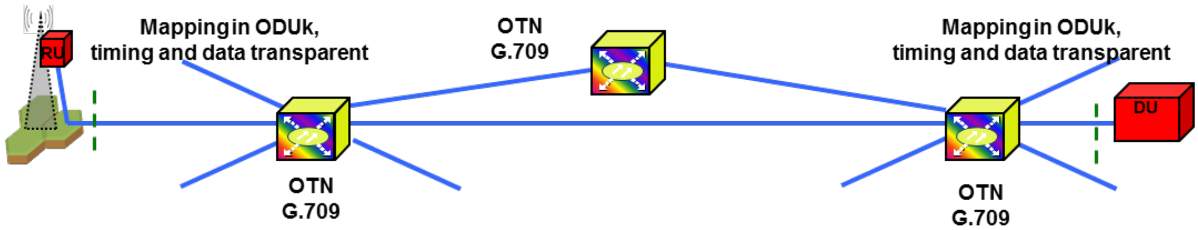


Figure 4-8: OTN

Mapping of the ORI/CPRI signal onto ODU introduces some delay and, in turn, reduces the maximum fiber length between RU and DU.

Signals of several RUs can be transported on separate wavelengths using OTU1 (2.5 Gbps) or OTU2 (10 Gbps) signals. One benefit of OTN is Forward Error Correction (FEC) which makes links less sensitive to bit errors and improves reach. However, as already mentioned, the fronthaul connection length is not limited by the transport technology. In the case of fronthaul, FEC will even reduce the achieved distance through introduced latency.

Signals of several cells can also be multiplexed and carried in OTU2. Moreover, mapping of mixed-signal configurations, including GSM, UMTS and LTE, into OTU should be considered.

Compression can reduce the required bandwidth in fronthaul by a factor of three. This will allow mapping the CPRI interface of an LTE RU into ODU0. However, multiplexing three LTE sectors will still require OTU2.

Summary

Provides a common and complete optical transport solution for native fronthaul transport

Pros	Cons
• Meets the strict jitter requirements of CPRI • Provides aggregation of CPRI links via ODU multiplexing • A complete networking solution • Scalable and manageable	• Transponder needed in addition to standard pluggables • In case of BH the entire 1 GbE is transported, i.e. no statistical multiplex gain

4.8 Case 8: XGPON and GPON

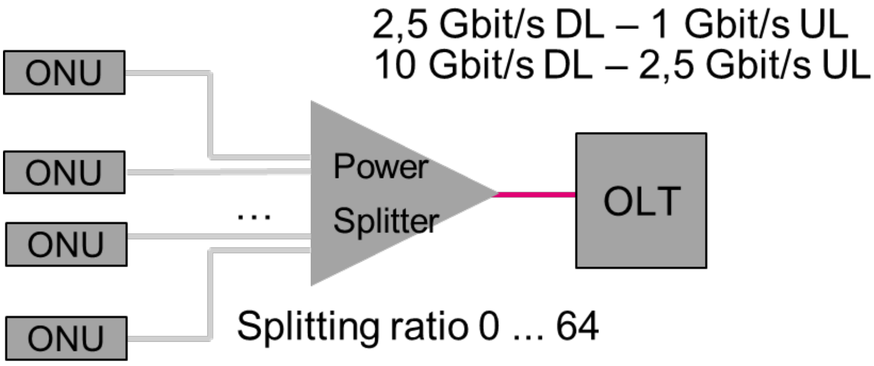


Figure 4-9: G-PON

GPON is used in connection with FTTH and is widely available in many urban areas. The optical budget of a typical GPON system limits distances between the central office and customer premises to approximately 20km. However, the factor which makes GPON impractical for fronthaul applications is the asymmetric and limited bandwidth. GPON is not sufficient even for one small cell (1.22 Gbps @10MHz 2x2 MIMO). XGPON could capture only one macro cell without compression. Also, reach limitations and increase of data rates would induce changes to infrastructure. GPON, XGPON and NGPON2 do not support circuit emulation. NGPON2 is specified for up to eight XGPON interfaces plus further point-to-point interfaces (10 GbE, CPRI, etc). However, NGPON2 and, in particular, the point-to-point interfaces are not yet available. It is too early to evaluate whether the point-to-point interfaces of NGPON2 will meet the requirements of fronthauling. However, GPON, XGPON and NGPON2 could be used for backhauling.

5 FRONTHAUL AS A SERVICE (MANAGED CPRI)

The first step in making fronthaul costs attractive is to define fronthaul as a service (*Managed CPRI service*). This will enable to widen C-RAN's addressable market. Self-owned fiber is a limited resource for many mobile operators. For the industry to break the linkage between self-owned facilities and C-RAN, vendors and service providers will need to improve the business case for fronthaul.

Fronthaul as a transport has stringent service-level requirements. By defining a set of guidelines and a clear definition of interface requirements for C-RAN fronthaul service levels, we can achieve the following:

- Enable sharing scenarios
- Create a secondary market for C-RAN fronthaul services
- Provide a smoother deployment environment for operators with self-owned transport facilities

To start the process of formalizing fronthaul as a service, we need to define the following elements:

- The user interface – to the RU or the DU – usually CPRI, however, in the future could be Ethernet
- The existence and the location of an optional CPRI compress/decompress function
- The existence and the location of an optional CPRI-to-Ethernet mapping function

The reference here is for CPRI, but this discussion can be expanded to any RU-DU interface such as ORI or OBSAI. For the sake of clarity, let us assume CPRI carrying a single LTE sector with 20MHz in 2X2 MIMO configuration, i.e., 2.5Gbps (to be precise, 2,457.6Mbps denoted CPRI line rate option 3).

With these base building blocks, we will try to develop a language and a model that service providers may adopt to offer fronthaul as a viable service.

5.1 Case 1: ORI/CPRI Native Transport Service

Case 1 deals with an end-to-end CPRI service that maps the CPRI onto an optical solution such as OTN, based on ITU specifications. We can also create a high-capacity; native CPRI service based on any of the transport solutions proposed in section 4. On the positive side, this case maintains the concept, implies less risk as a service and doesn't require any changes from the RU or the DU. On the negative side, operators might find that high-capacity OTN services are less available and more expensive, underscoring the purpose of our quest: finding a cost-efficient way to provide fronthaul.

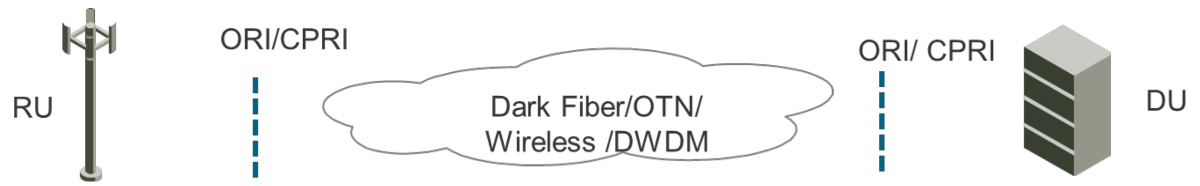


Figure 5-1: ORI/CPRI Native Transport Service

Summary

- End-to-end ORI/CPRI service
- ORI/CPRI in, ORI/CPRI out
- For OTN, standard ORI/CPRI over OTN as defined in ITU-T G.709

Pros	**Cons**

• Maintains the same concept • Implies less risk as a service • No impact on RU or the DU	• High-capacity services are less available and more expensive • Requires a new CPRI interface in the transport gear

This case once defined properly, can expedite deployment of C-RAN in a self-owned fiber environment or within places where there exists a significant quantity of fiber-based service providers who can add CPRI interfaces into their service offering.

5.2 Case 2: "Pseudo" ORI/CPRI Service

Case 2 deals with an end-to-end CPRI service as well. It differs from Case 1 in that, this time, we're mapping onto an Ethernet service. This is where we will need the CPRI-to-Ethernet Mapping Function (CEMF). On the positive side, Case 2 maintains the same concept — it doesn't require any changes from the RU or the DU while Ethernet services are common. On the negative side, operators will need stringent-SLA Carrier Ethernet networks which are not as common and are more expensive, thus requiring a new CPRI/CE interface and mapping guidelines.

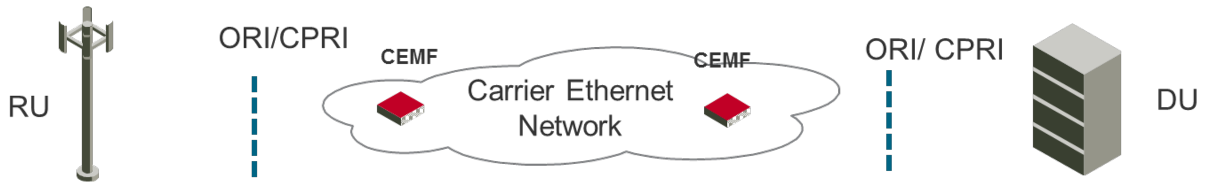


Figure 5-2: "Pseudo" ORI/CPRI Service

Summary

- End-to-end CPRI service
- ORI/ CPRI in / ORI/CPRI out
- Map CPRI over an Ethernet service

Pros	Cons
• Maintains the same network concept • No impact on RU or the DU • Ethernet services are common	• Stringent-SLA Carrier Ethernet networks are not common and are more expensive • Requires a new CPRI/CE interface in the Carrier Ethernet gear • Requires mapping guidelines and more strict timing

5.3 Case 3: Ethernet Service

In Case 3, the RU and DU do the CEMF, allowing for direct connection into an Ethernet service. Obviously, native Ethernet services are more common, but this scenario brings a new set of development into the RAN equipment with a longer roadmap, or it can be undertaken by a 3rd party.

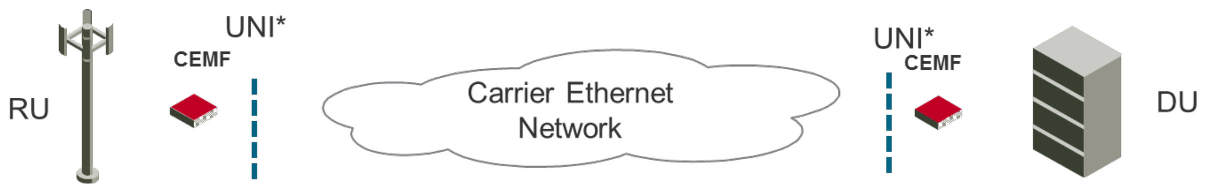


Figure 5-3: Ethernet Service

Summary

- Ethernet in / Ethernet out

- Map ORI/CPRI over Ethernet at the DU/RU level (proposed in advanced version of CPRI and ORI)

Pros	Cons
• Ethernet services are common	• Stringent SLA CE networks are not as common and are more expensive • Requires new DU/RUs and net concept • Requires mapping guidelines

5.4 Service Latency Considerations

At this point, you may be wondering about latency and how Cases 2 and 3 can cope within the Ethernet technology.

CPRI designers considered an end-to-end propagation delay equal to 20km on fiber. On top of that, there is the inherent store-and-forward delay based on capacity: 12usec for 1Gbps and 1.2 for 10Gbps. A 1Gbps link can carry uncompressed 10MHz of access spectrum. We can envision a transport network with 1 or 2 hops of 1Gbps feeding into a backbone of 10Gbps or more to the centralized DU site. So, considering latency, this is definitely a plausible path. However, it needs to be researched further since not all CPRI-based elements today can tolerate a latency of 100usec. As the industry target for fronthaul latency is set for 250usec (one way), it gives more leeway for service providers to offer a managed-CPRI service. While latency seems to be covered in the roadmap, CPRI comes with challenging, strict jitter requirements.

The other issue is that the magic number in C-RAN models today is actually ~2.5Gbps that can carry a single radio unit with 20MHz, 2X2 MIMO. This raises the need for compression, denoted in the figure below as CCDF, short for CPRI Compress-Decompress Function.

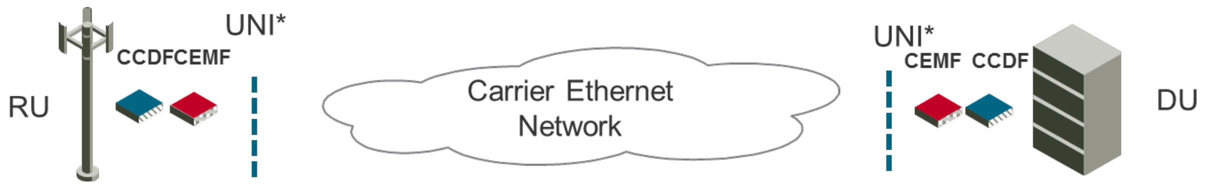


Figure 5-4: Ethernet Service with Compression

Adequate compression that is transparent to the RU-DU level improves the chances of finding an affordable service for the RU. In addition, there might be some interoperability tests to verify that this compression won't impact the control part of the CPRI. Essentially, compression is still further away from realization. Various organizations including NGMN, 3GPP, ETSI ORI and CPRI discuss different ways to reduce the capacity and latency requirements to make deployment easier in the longer term.

Though CPRI bit-streams are constant-rate, it is not impossible to make a compressor for them that would see a variable gain. Two methods for doing this are using knowledge of when the cell is scheduled and (on the uplink) using the correlation between nearby receivers to do joint compression (likely also informed by the scheduler). Basically, even though we have a CPRI stream, one might be able to get split processing-style gains out of a compressor for it if the compressor has additional knowledge about what is happening on the air-interface

C-RAN promises to change the equation of cost and capacity even though it is currently limited by the availability of reasonably priced fronthaul options. By implementing small or large clouds using RUs or pico RUs, operators are expected to deliver a better user experience at a lower total cost.

5.5 Compression at the transport level

Few more words on the compression and whether it is also possible to apply the CCDF function at the transport layer. Since it is expected to be part of the RU and DU and future CPRI interfaces would probably come with reduced capacity requirements, this case applies to the install base cases. In places where transparent fronthaul bit stream transport is not possible or not economically viable, an optional CPRI Compress/ Decompress Function (CCDF) may to be used as long as it meets the following transparency requirements (Figure 5-5):

- Limited signal degradation below EVM of 3%[4].
- Additional latency due to compression should still meet fronthaul latency requirements
- Support the strict jitter requirements that CPRI specifies
- Maintain CPRI specification clock and timing
- Keep the integrity of CPRI specification overheads
- Suppress unpopulated antenna-carrier (AxC)
- Address Multi-RAT support
- Can generate a 50% gain, at least

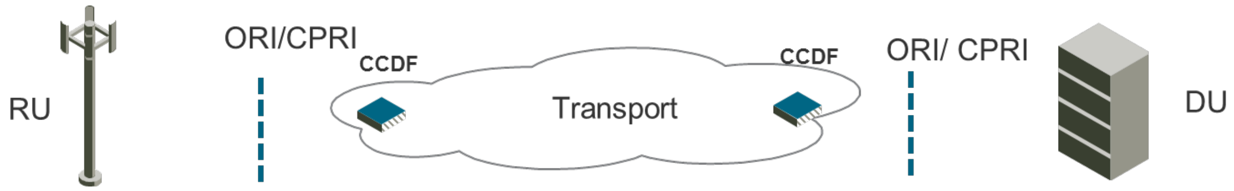


Figure 5-5: ORI/CPRI Transport with Compression

Summary

- End-to-end ORI/CPRI service
- ORI/CPRI in / ORI/CPRI out
- Uses at least 50% less transport capacity for the same requirement

Pros	Cons
• ~2-3 times more utilization • Maintains the same concept • Implies less risk as a service • No impact on RU or DU	• CCDF is not completely transparent • High-capacity transport services are less available and more expensive • Requires a new CPRI/transport interface • Can optimize transport based on traffic awareness

5.6 Need for DU hoteling facilities as a service

Another point where C-RAN might be less relevant for challenger mobile operators as opposed to incumbents, is the need for centrally located DU Hoteling facilities. While incumbents can use some of the central offices (CO) to host the DUs and those usually are located a short distance from subscribers and cell sites. This network topology can be also used for the fronthaul. Challengers need to extend their footprint which is traditionally built outside of the major cities in lower real-estate locations making them less relevant for DU hoteling and more complex to provide fronthaul in terms of the number of fiber connections and distance. Moreover, most challengers kept their number of core sites to the minimum

[4] 3% is referenced in the ORI work and represents less than 1 dB degradation that is reasonable figure to assume for the total distortion budget defined in 3GPP 36.141

making their networks less scalable to handle C-RAN requirements. To summarize the issue of leasing fronthaul services, for challengers, the service might start at the RU site and end up at a hosted DU hotel which is part of the service, and then backhauled to the core of the operator.

6 CONCLUSIONS

The evolution of RAN technologies and associated architectures presents a number of questions with regard to the future of mobile backhaul and introduction of fronthaul. MNOs' responses to these questions will differ based upon their situation as regards access to fibre infrastructure. The key difference is between incumbent fixed operators with mobile network operations and mobile-only competitive operators, reliant on third-party Ethernet leased lines and/or microwave.

RAN vendors are working on enhanced performance for traditional D-RAN in parallel with the introduction of C-RAN solutions. Operators will find the optimal solution for their network based upon technical and economic considerations. It is anticipated that C-RAN gains will improve over time and may become quite compelling in high-traffic urban areas. A range of fronthaul products will be required to address all the scenarios. These will range from dark fibre to managed CPRI and wireless solutions, particularly in the millimetre-wave bands.

It is highly likely that operators will maintain parallel backhaul and fronthaul networks. Great flexibility will be required in the design of such networks to ensure seamless and cost-optimised migrations. CWDM technology will certainly have a significant role to play as operators enhance fibre-based connectivity and scale hybrid backhaul/fronthaul and all-fronthaul solutions. The role of wireless fronthaul will provide operators with a flexible solution for short hops and may be used effectively with fibre as a range extender or cost-optimised final tail.

7 REFERENCES

The complete range of access solutions and the different ways one may implement them in the network are described in other recent NGMN documents. For the transport, known as backhaul and fronthaul, there are several documents covering the subjects. Here are just a few:

- Backhaul Provisioning for LTE-A & Small Cells Backhaul
- Deployment Scenarios (New Revision)
- Security In LTE Backhauling
- Integrated QoS Management
- Fronthaul requirements for C-RAN
- P-RANEV: CoMP Workstream (Ideal and non ideal Backhaul requirements)

Other recommended references from bodies dealing with similar issues:

- MEF 22.1 [5]- Implementation Agreement Mobile Backhaul Phase 2
- BBF TR-221[6] - Technical Specifications for MPLS in Mobile Backhaul Networks
- Common Public Radio Interface (CPRI) Interface Specification [7]
- ETSI Open Radio equipment Interface (ORI)[8]

8 ACKNOWLEDGEMENTS

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9 GLOSSARY OF DEFINITIONS AND TERMS

3GPP	3rd generation partnership project
AxC	Antenna-Aarrier
BH	Backhaul
BTS / eNB	Base Station / Enhanced Node B – An LTE BTS
C-RAN	Centralized/Collaborative/Cloud/Clean Radio Access Network
CoMP	Coordinated Multipoint Processing – A range of LTE-A techniques including Joint Transmission (JT) Joint Scheduling (JS), Joint Reception (JR), Coordinated Beamforming (CB) and many more

[5] http://metroethernetforum.org/Assets/Technical_Specifications/PDF/MEF_22.1.pdf
[6] http://www.broadband-forum.org/technical/download/TR-221_Amendment-1.pdf
[7] http://www.cpri.info/spec.html
[8] http://portal.etsi.org/tb.aspx?tbid=738&SubTb=738

CA	Carrier Aggregation - LTE-A feature
CCDF	CPRI Compress/ Decompress Function
CE	Carrier Ethernet
CEMF	CPRI-to-Ethernet Mapping Function
CO	Central Office
CPRI	Common Public Radio Interface – promoted by CPRI.org
CSG/CSR	Cell Site Gateway/Router
D-RAN	Distributed RAN
DL	Downlink
DU	Radio Unit – also referred as Base Band Unit (BBU)
eICIC	Enhanced Inter Cell Inference Cancelation
EVM	Error Vector Magnitude - Sometimes also called Receive Constellation Error (RCE)
FEC	Forward Error Correction
FH	Fronthaul
HARQ	Hybrid Automatic Repeat Request
Hetnet	Heterogeneous network
ICI	Inter-Cell Interference
LTE/LTE-A	Long Term Evolution / Advanced
UL	Uplink
MO	Multi Operator (As in shared network)
MNO	Mobile Network Operator
ORI	Open Radio Interface – promoted by ETSI ORI
OTN	Optical Transport Network
OTU/ODU	OTN information structures
PON / GPON	Passive Optical Network
PoP	Point Of Presence
QoE	Quality of Experience
QoS /HQoS	(Hierarchical) Quality of Service
RAT	Radio Access Technology
RU	Digital Unit – Also referred as– Remote Radio Heads (RRH)
SFP/XFP	Small Form-factor Pluggable / 10 Gbps SFP
SLA	Service Level Agreement
SO	Single Operator
TDM	Time Division Multiplexing
Tx	Transport element
xWDM/CWDM	Wavelength Division Multiplexing (C- Coarse / D-Dense/P-Passive)