Towards a Flexible Functional Split for Cloud-RAN Networks

Andreas Maeder[1], Massissa Lalam[2], Antonio De Domenico[3], Emmanouil Pateromichelakis[4], Dirk Wübben[5], Jens Bartelt[6], Richard Fritzsche[6], Peter Rost[1]

[1]NEC Laboratories Europe, [2]Sagemcom Broadband, [3]CEA-LETI, [4]University of Surrey, [5]University of Bremen, [6]Technical University of Dresden

***Abstract*—Very dense deployments of small cells are one of the key enablers to tackle the ever-growing demand on mobile bandwidth. In such deployments, centralization of RAN functions on cloud resources is envisioned to overcome severe inter-cell interference and to keep costs acceptable. However, RAN backhaul constraints need to be considered when designing the functional split between RAN front-ends and centralized equipment. In this paper we analyse constraints and outline applications of flexible RAN centralization.**

Keywords—5G; Cloud RAN; LTE; backhaul; functional split

I. Introduction

The evolution towards 5G mobile networks is characterized by an exponential growth of traffic due to the increased number of user terminals, richer internet content, more frequent usage of internet-capable devices, and by more powerful devices. To handle regional and temporally fluctuating traffic patterns in combination with different terminal classes and diverse services, flexible scaling possibilities in mobile networks are required. In contrast, current mobile networks are not able to efficiently support this diversity and are designed for peak-provisioning and typical internet traffic. The use of very dense, low-power, small cell networks with very high spatial reuse is a promising way to allow for handling future data rate demands [1]. Small cells reduce the distance between the base station (BS) and the user equipment (UE) and allow for reusing the spectrum by neighbouring BSs. Small-cells complement existing macro-cellular deployments which are required to provide coverage for fast-moving users and in areas with low user-density. In 3GPP LTE, small cells draw significant attention both on physical [2] and higher layer [3] where impacts on the radio access network (RAN) protocol and system architecture are discussed.

As networks become denser, interference scenarios become more complex due to multi-cell interference. Centralized processing permits the implementation of efficient radio resource management (RRM) algorithms which allow for radio resource coordination across multiple cells. It also allows for optimization of the radio access performance at signal-level, e.g., through joint multi-cell processing and inter-cell interference coordination (ICIC). Cloud-RAN or centralized-RAN (C-RAN) is one possible way to efficiently centralize computational resources, and it has recently attracted a great deal of attention [4]. In C-RAN, multiple sites are connected to a central data centre where all the baseband (BB) processing is performed. However, C-RAN has very high requirements on the link between the Remote Radio Heads and the central processing unit in terms of capacity and latency, such that only optical fibre is a suitable choice for deployment. This contradicts with the expectation that future small cell networks will use a heterogeneous set of backhaul technologies, depending on factors such as cost, regulations, and availability.

In order to address the trade-off between centralization and backhaul requirements, and to increase the applicability of the C-RAN paradigm, we propose to implement a *flexible functional split* between a centralized network entity and radio front ends as shown in Fig. 1.

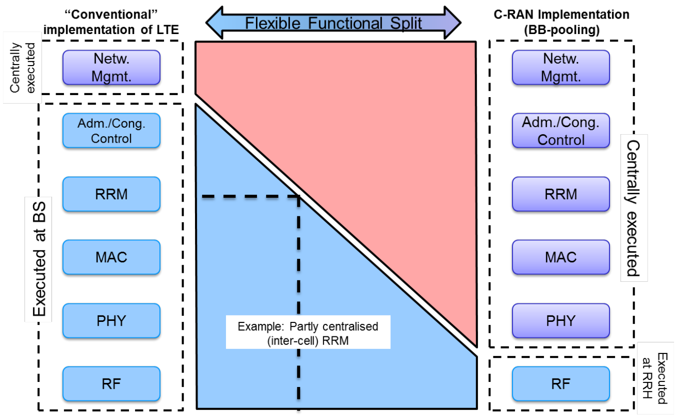


Fig. 1. Flexible functional split for cloud RAN

In our vision, flexible functional split is a main enabler for future generations of cellular networks [5]. Adapting the degree of centralization in signal processing and resource management functionalities to the actual service requirements and constraints will enable to greatly enhance network performance and system efficiency. To this end, we will analyse the system constraints from backhaul and RAN implementation point of view, and show exemplarily how different functional split configurations could be utilized depending on the transport network characteristics. In Section II, system constraints and requirements are analysed, creating the solution space for the functional split. In Section III, example configurations are described, and Section IV lists challenges and gives an outlook.

II. SYSTEM REQUIREMENTS AND CONSTRAINTS

From a technical perspective, the applicability of C-RAN is defined by constraints and requirements imposed by the backhaul on the one hand, and RAN on the other hand. As elaborated in the next subsection, backhaul constraints are the result of different technological approaches, topologies, and transmission media, i.e. wired and wireless backhaul. These constraints need to be matched by RAN requirements on bandwidth and latency, as analysed in subsection II.B. Consequently, depending on the backhaul constraints and RAN requirements, a certain functional split configuration is possible, with corresponding centralization benefits for system performance.

A. Backhaul Technologies and Constraints

1) Wired backhaul

Wire-line backhaul relies mostly on two physical mediums: copper and optical fibre.

Copper-based: Considering copper-based solutions, leased T1/E1 copper lines are extensively used in cellular systems as they can provide suitable support for voice traffic, with deterministic QoS, low latency, and jitter. However, copper lines do not scale easily to provide adequate bandwidth at distances exceeding few hundred meters to support emerging broadband technologies [6]. Even with 8-pair bonding and vectoring VDSL2 technology, the bandwidth is limited to around 140 Mbps in the upstream [7].

Fibre-based: On the other hand, optical fibre can provide a multi-Gbps throughput connectivity that can be achieved using gigabit passive optical network (GPON) technologies [8]. Optical fibres are usually deployed in urban and sub-urban areas where very high traffic-carrying capacity is more than required. Although a fibre-based backhaul offers long-term support with respect to increasing capacity requirements, this comes at a relatively high CAPEX and costly deployment.

2) Wireless backhaul

Various wireless backhaul solutions exist in terms of the type of propagation, the spectrum used and the network topology. In general, the advantage of wireless backhaul is the freedom from cabling, which is expensive to deploy due to the high costs. Wireless solutions need only equipment at the small cell and the Point of Presence[1] (PoP) offering reduced costs and speed of deployment. The main categories are the following:

Sub-6 GHz: This category can be seen as a '*Non Line of Sight'* category and includes carrier frequencies below 6 GHz (3.5 GHz licensed and 2.4 / 5.8 GHz unlicensed). Sub-6 GHz backhaul can be easy to plan and deploy in urban areas, thereby significantly reducing the cost and duration of small cell network roll out. In particular, the 3.5 GHz band has emerged as a promising candidate for the dedicated use of small cells. On the other hand, the unlicensed spectrum provides a large amount of freely available bandwidth but is likely to be already (or later) heavily used by Wi-Fi hotspots, Bluetooth, and other equipment.

[1] Points of Presence are defined as logic entities which offer connectivity to the core network for small-cells.

Free-space optical (FSO): FSO backhaul is a line of sight (LoS) technology that uses invisible beams of light to provide optical bandwidth connections at multi-Gbps rates [9]. FSO uses the same transmission wavelengths as fibre optics (850 nm, 1550 nm) but transmits over the air. Its fundamental similarities to fibre optic make it a strong candidate to support future packet-centric networks. However, its main drawback is the requirement of high-stability mounting and the dependency on obstructions and fog attenuation.

Microwave backhaul: Microwave radio can be seen as an alternative choice of backhaul connectivity especially in areas where a wired connection is not available. Microwave transmission operates mainly in licensed spectrum (6 GHz to 38 GHz) and requires LoS (or near-LoS) [6]. In general, microwave radio can provide capacity of some hundred Mbps [10] and high availability especially in higher bands.

Millimetre wave (mmW) radio: Conceptually mmW-radio refers to any RF technology operation in the 30-300 GHz range, but it is generally used to discuss 60-80 GHz, also known as "E-band" [11]. In this context, several GHz-wide bandwidths are available and can provide multiple Gbps even with low-order modulation schemes. In addition to these high-data rates, mmW radio band can offer excellent immunity to interference, high security, and the reuse of frequency. However, mmW radio requires clear LoS propagation and its range is restricted by the oxygen absorption which strongly attenuates ≥60 GHz signals over distances. Therefore, high gain directional antennas are used in order to compensate for the large free space propagation losses.

TABLE I. BACKHAUL CLASSIFICATION [12]

BH technology	**Latency (one-way)**	**Throughput**
Ideal fiber access	2.5 μs	10 Gbps
Fiber Access 1	10 ms – 30 ms	10 Mbps – 10 Gbps
Fiber Access 2	5 ms – 10 ms	100 Mbps – 1 Gbps
DSL Access	15 ms – 60 ms	10 Mbps – 100Mbps
Cable	25 ms – 35 ms	10 Mbps – 100 Mbps
Sub -6 GHz Wireless	5 ms – 35 ms	50 Mbps – 100Mbps
Microwave	< 1 ms	100 Mbps – 1 Gbps
mmW radio	< 1 ms	500 Mbps – 2 Gbps

3) Topology

Generally, there are two main topology types for wireless backhaul technologies: 1) *Point-to-Point (PtP)* and 2) *Point-to-Multipoint (PmP).* In PtP, individual point to point links between nodes (i.e. access points and / or gateways) can be interconnected to form chain, tree, ring or mesh topologies [8], whereas in PmP a PoP forms multiple links to a number of access points. The main challenges of PtP are: a) the large number of antennas that may be required at the PoPs; b) the requirement for frequent re-planning whenever new nodes are added; c) the inclusion of redundant links offering resiliency to link outages and; d) multi-hop links can lead to latency restricted performance. On the other hand, PmP links may be more efficient to pool resources across a larger, changing number of nodes and average out any difference in traffic demand at different times of day. Table I summarizes some key features of the discussed backhaul technologies, based on the classification described in [12].

B. 3GPP RAN System Requirements

1) Bandwidth requirements

The bandwidth required for backhauling between a base station and the cloud platform generally depends on a large number of parameters, such as the number of sectors, the number of carriers, the bandwidth of the carriers, and the load of BSs. In addition, it depends on the functional split itself [13], [14]. Fig. 2 shows different options to split PHY layer functionality of the UL processing chain between BSs and the cloud platform. Table II lists the corresponding data rates for some exemplary parameters [14]. Note that similar observations can be made for the downlink, only the processing order is inversed. In general, we can observe that the greater the degree of centralization, the higher is the required backhaul bandwidth. The difference can be as high as factor 100 between different split options.

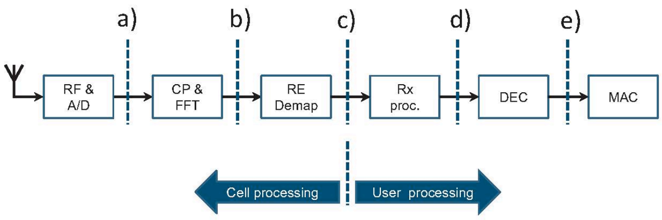


Fig. 2. Functional split options for the PHY layer

These different requirements in combination with the actual capacity provided by the backhaul technologies deployed have to be considered when deciding for a certain functional split. In cases of congested backhaul it might even become necessary to reduce the degree of centralization to be able to backhaul all traffic. It also becomes clear that for high degrees of centralization only high capacity backhaul technologies such as fibre and E-band radio can be considered.

TABLE II. REQUIRED BH CAPACITY FOR UL SPLIT OPTIONS

Split	Required bandwidth	In % of a)
a) I/Q Forwarding	2,457 Mbps	100.0 %
b) Subframe forwarding	720 Mbps	29.3 %
c) Rx Data forwarding	360 Mbps	14.7 %
d) Soft-Bit forwarding	180 Mbps	7.3 %
e) MAC Data	27 Mbps	1.1 %

2) Latency requirements

Beside bandwidth requirements, also latency requirements need to be fulfilled by the backhaul for different functional split options. Since 3GPP defines many timers from the MAC to the RRC layer, these values will ultimately define the maximum latency requirement needed per layer enabling a transparent functional split, i.e., without any specification changes.

In LTE, the PHY layer works with 1 ms subframe granularity. At the MAC layer, the HARQ timing is the most critical one. Once a subframe has been sent at subframe *n* for a given HARQ process, an acknowledgement (positive or negative) is expected at subframe *n*+4. Due to the synchronous nature of HARQ in the uplink, any functional split at the base station MAC layer requires the round-trip time plus the processing to be done in 3 ms. Backward compatible solution exists to delay the retransmission but this will stall the HARQ process at the same time, reducing the throughput [13].

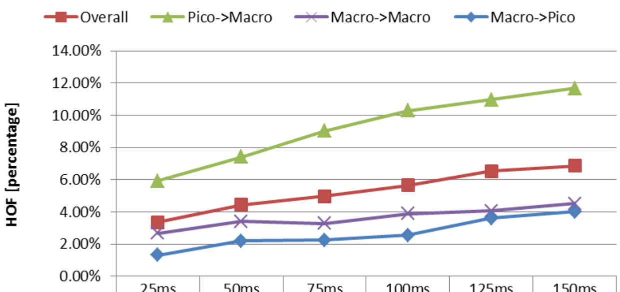
Table III shows the main specified timers and timing constraints per layer which may impact the functional split. Apart from the MAC timer previously discussed, the other timers offer sufficient timing range to be configured to account for the backhaul latency enabling a functional split above the MAC layer without too many difficulties from implementation and system performance perspective. Nevertheless, these timers impact the overall system performance and require careful tuning to avoid performance degradations.

TABLE III. 3GPP TIMING REQUIREMENTS

	Timer	Short description	Max Value
PHY	Subframe	Physical subframe length	1 ms (fix)
	Frame	Physical frame length	10 ms (fix)
MAC	HARQ RTT Timer	When an HARQ process is available	8 ms (fix)
RLC	t-PollRetransmit	For AM RLC, poll for retransmission @tx side	500 ms
	t-Reordering	For UM/AM RLC, RLC PDU loss detection @rx side	200 ms
	t-StatusProhibit	Prohibit generation of a status report @rx side	500 ms
PDCP	discardTimer	Discard PDCP SDU / PDU if expiration or successful transmission	Infinity
RRC	TimeToTrigger	Time to trigger of a measurement report	5.12 s
	T300	RRCConnectionRequest	2 s
	T301	RRCConnectionReestablishmentRequest	2 s
	T304	RRCConnectionReconfiguration	2 s or 8 s
	T310	Detection of physical problem (successive out-of-sync from lower layers)	2 s
	T311	RRC connection reestablishment (E-UTRA or another RAT).	30 s

3) Protocol aspects

In addition to bandwidth and latency requirements particularly implied by lower layers, the RAN protocol stack imposes certain dependencies and requirements which need to be considered. This applies especially if the functional split is implemented at higher layers. The first function of interest is cell reselection. Cell reselection is located in the RRC layer and belongs to the control plane protocol stack. This process allows for selecting for each UE the best cell that can serve it. For this purpose, each UE measures the received signal strength of the different surrounding cells. Based on these values, the UE RRC (in idle mode) or the BS RRC (in connected mode) will select the strongest one from the list and will initiate the cell reselection/handover procedure.



	25ms	50ms	75ms	100ms	125ms	150ms
Overall	3.35%	4.43%	4.98%	5.64%	6.53%	6.87%
Pico->Macro	5.93%	7.43%	9.04%	10.30%	10.97%	11.69%
Macro->Macro	2.68%	3.41%	3.28%	3.89%	4.07%	4.51%
Macro->Pico	1.30%	2.21%	2.25%	2.54%	3.60%	4.00%

Fig. 3. Impact of latency on hand-over failure rate (HOF)

The main challenge of the cell (re)selection process is that the current associated mechanisms are based solely on the power level received from neighbouring cells, without using information regarding the cell loads and backhaul capacities. Fig. 3 illustrates an example of the impact of backhaul latency on the performance of cell reselection, here in the case of handover due to mobility: It can be observed that a higher backhaul latency increases hand-over preparation time, which leads to an increasing handover failure rate, especially in case of pico-to-macro cell handovers. This is especially a challenge in dense networks due to the increased hand-over rate. While corresponding timer values can be adjusted individually for each deployed small cell (e.g., TimeToTrigger as listed in Table III), this approach does not seem suitable for large deployment scenarios.

Segmentation and reassembly located in the RLC layer are also functions of interest to be considered. The RLC layer is, together with the PDCP layer, responsible for the link reliability functionality such as re-transmissions and re-ordering. The first challenge is the backhaul reliability and its impact on the 3GPP performance. One possibility is to handle errors using standard mechanisms on the RLC layer even though this implies unnecessary overhead on the wireless interface between user terminal and base station. An alternative solution is to retransmit on the backhaul in order to reduce both delay and overhead on the wireless link. The second challenge is jitter on the backhaul link which adds up to the end-to-end jitter. Hence, the timers maintained by the base station may need to be adjusted in order to compensate the increased jitter. In particular, the base station needs an interface to the network controller in order to receive an estimate of the jitter on the backhaul link. Alternatively, queues can be used to remove potential jitter induced by the backhaul. However, the queue needs to be dimensioned carefully to avoid large additional latency.

Finally, the MAC layer defines how much data is taken from RLC queues into MAC transport blocks, depending on channel conditions and available resources. If the latency on the backhaul link is low, there is no significant impact. However, in the case of high backhaul latency, the actual preferred link adaptation and therefore transport block size of the MAC layer may be outdated at the point in time when RLC prepares the PDU for the MAC layer. This can lead to an increased outage and re-transmissions due to imperfect link adaptation. Besides HARQ, also a more conservative choice of MCS may solve the problem but at the cost of a lower throughput. This is illustrated in Fig. 4 for three different values of imperfect channel state information at the transmitter (CSIT, represented by ε) and an SNR of 15dB. The figure shows that with an increasingly imperfect CSIT, the chosen rate needs to be reduced in order to match the required low outage probability in LTE of 1-10%.

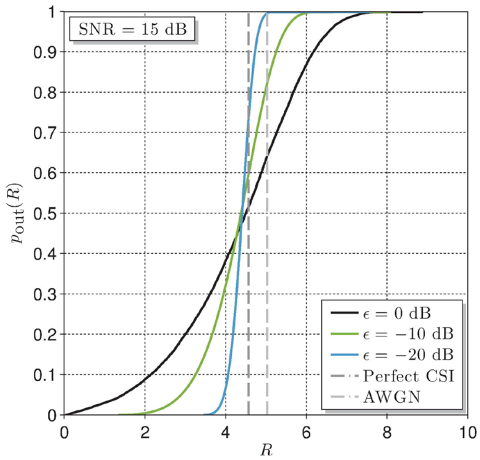


Fig. 4. Outage probability and average rate under different imperfect CSIT and block Rayleigh fading

III. Applicability of Functional Split Configurations

In general, coordination, even locally, comes at a cost of increased complexity, overhead, and energy consumption. Furthermore, it may not be compatible with the momentary service constraints, system timing requirements, and actual backhaul performance in terms of capacity, latency, and reliability. Additionally, the expected centralization benefits do not always counterbalance the associated costs. For instance, in lightly loaded conditions, the average level of interference is low, and ICIC mechanisms may not be required. Therefore, there is a need for adaptive mechanisms able to decide the level of feasible coordination leading to system improvements. Accordingly, three main functional split configurations can be identified at PHY, MAC, and RRC. Each one is associated with given requirements, potential gains, and implementation challenges (see Table IV).

A. Functional Split on PHY layer

Functional split on PHY layer enables to fully exploit spatial diversity and by implementing advanced signal processing mechanisms, inter-cell interference can be mitigated or even exploited to increase the overall network capacity. When full coordination is realized, functional split at PHY coincides with the classic centralized RAN architecture [4].

TABLE IV. REQUIREMENTS, BENEFITS, AND CHALLENGES OF FUNCTIONAL SPLIT OPTIONS

Functional split	Centralization requirements	Centralization benefits	Challenges
PHY	Low-latency high-capacity backhaul required for full coordination; flexible requirements in partial coordination options	Spatial diversity gains, Interference mitigation/cancellation	Finding the optimal trade-off between full and partial coordination; amount of exchanged information must scale accordingly.
MAC	Low-latency backhaul required for full coordination; flexible requirements in partial coordination options	Enhanced spectral efficiency; Interference mitigation	Dynamic ICIC can be a challenge in a highly loaded scenario.
RRC	Backhaul constraints can be relaxed	Optimized load balancing and mobility management; improved energy efficiency	Finding optimal solutions can be challenging and computationally complex in dense deployment scenarios

However, most of the PHY cooperative mechanisms require tight synchronization and the exchange of soft information, which can be realized only with low-latency high-capacity backhaul links. To solve this complexity issue, we are currently investigating different PHY enablers that exploit functional split for flexible coordination amongst neighbouring cells [15]. For instance, in-network processing [17] and multi-point turbo detection enable multi-user detection (MUD) [15], where the processing of the received signals related to distinct UEs is realized in a coordinated way to increase the overall network throughput. In the same way, coordinated pre-coding can be implemented to enable effective inter-cell interference coordination. These schemes adapt their functionalities to the system characteristics: in low backhaul capacity conditions, the signalling is minimized and processing is mainly realized locally. On the contrary, when the backhaul constraint is relaxed, full coordination is implemented and higher performance can be achieved without compromising the system reliability.

B. Functional Split on MAC layer

Functional split can also be realized at the MAC layer to enable coordinated RRM and centralized scheduling [16], which is closely coupled with dynamic inter-cell interference management, and more specifically to interference coordination. ICIC has the task to manage radio resources such that inter-cell interference is kept under control. ICIC is inherently a multi-cell RRM function that needs to take into account the resource usage status and traffic load situation of multiple cells. The preferred ICIC method may be different in the uplink and downlink. This approach increases the overall system spectral efficiency by mitigating inter-cell interference and exploiting multi-user diversity. The backhaul capacity requirements associated with a full centralized RRM approach is still high, since sharing channel state information is necessary to correctly implement, i.e., multi-cell scheduler. Moreover, performance depends also on the backhaul latency, since outdated channel state information (CSI) strongly limits the achievable gains, as illustrated in Section II.B.3.

In LTE, dynamic inter-cell interference management is supported based on messages exchanged between neighbouring cells over the X2 interface. In general, there are two main options to perform inter-cell RRM in a centralized environment. The first option is to perform the resource allocation centrally to minimize inter-cell interference. The actual schedule is then exchanged with the small-cells. The second option is to only resolve inter-cell interference conflicts, i.e. small-cells perform local scheduling and in the case of significant inter-cell interference, a coarse-gain central schedule is performed and exchanged with the small cells. The performance of the first option is higher but it also imposes stronger requirements on the backhaul latency. By contrast, the second option, which represents a two-stage scheduling approach, copes with higher backhaul latency while preserving a major part of the gains. Coordinated Radio Resource Control

Coordinated RRC enables to deal with user mobility, to optimize cell load, and to perform cell activation/deactivation mechanisms for energy saving purposes. The PHY/MAC adapting mechanisms are implemented in short-time scale (from milliseconds to below one second) to reply to fast changes due to the channel conditions and traffic. However, coordinated RRC operates often on a multi-second basis, and it is characterized by less stringent constraints in terms of required overhead and timing.

Hence, centralization could provide high gain through holistic network optimization. This centralization would not impose strong latency requirements on the backhaul. In the iJOIN framework, a coordinated load balancing mechanisms has been proposed to distribute the cell load amongst neighbouring cells by jointly taking into account the radio access and the backhaul capacity [16]. This approach results in notable throughput improvement, especially in highly loaded scenarios. Moreover, a mechanism to control the cell activity has been introduced to enhance the system energy efficiency. Neighbouring cells and their backhaul links are switched-on and off, according to the actual cell load and QoS constraints. Note that in both these solutions the RRM and the lower functionalities are locally implemented at each small cell.

IV. CONCLUSION AND OUTLOOK

RAN centralization is a promising technology to tackle some of the most urgent challenges for very dense small cell networks. For widespread application, the requirements of C-RAN on backhaul capabilities need to be relaxed. A flexible functional split increases the applicability by adapting the requirements of centralization to the actual capabilities of the backhaul network.

In the future, the technical challenges, especially architectural and implementation aspects of flexible functional split need to be addressed while at the same time retaining compatibility with existing LTE RAN specifications.

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