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D4.2

Network-layer algorithms and network operation and management: candidate technologies specification

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Abstract

This deliverable provides the complete description of the network layer Candidate Technologies (CTs) that have been developed by WP4 in order to allow for the support of different functional splits between iSCs and RANaaS entities, as well as to operate jointly the access and backhaul network in order to optimise the radio access network performance. These CTs are intended to provide solutions to the technical issues posed by the iJOIN objectives that cannot be properly addressed with actual architectural solutions. They also constitute the basis of the functional architecture developed by the WP, which is also described in full detail in the deliverable.

Prior to the CT description, the deliverable provides a characterisation of the transport network, in terms of capacity, latency and other KPIs, expected to be supported by the iJOIN architecture. This characterisation is used as an input to other WPs and considered in the evaluation of their CTs.

Although the report on the evaluation of the different CTs proposed is the objective of the final WP4 deliverable, to be issued in six months' time, the present deliverable provides a description of the evaluation methodology to be used. It should be noticed that both simulations and proof of concept systems will be used for these purposes. The deliverable also addresses the issue of compatibility between the different CTs in order to achieve the high level objectives defined by the project. Solutions for potential conflicts are provided. Finally, the deliverable reports on the development of a cost analysis model in order to evaluate the economic viability of the proposed technical solutions.

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Table of Contents

List of Figures

List of Tables

Abbreviations

3GPP	3rd Generation Partnership Programme
API	Application Programming Interface
BS	Base Station
CWDM	Coarse Wavelength Division Multiplexing
DMM	Distributed Mobility Management
DSL	Digital Subscriber Line
ECN	Explicit Congestion Notification
eNB	Evolved Node B
EPS	Evolved Packet System
FDD	Frequency Division Duplexing
GPRS	General Packet Radio Service
GTP	GPRS Tunnelling Protocol
IETF	Internet Engineering Task Force
iJOIN	Interworking and JOINt Design of an Open Access and Backhaul Network Architecture for Small Cells based on Cloud Networks
iLGW	iJOIN Local Gateway
iNC	iJOIN Network Controller
IP	Internet Protocol
IT	Information Technology
iveC	iJOIN virtual eNodeB Controler
LOS	Line Of Sight
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MN	Mobile Node
MPLS	Multiprotocol Label Switching
NLOS	Non Line Of Sight
OAM	Operations, Administration, Maintenance
ONF	Open Networking Foundation
OPEX	Operational Expenditures
OSPF	Open Shortest Path First
PDN	Packet Data Network
P-GW	Packet Gateway
PON	Passive Optical Networks
PQ	Phantom Queue
PtP	Point-to-Point
PtmP	Point-to-multiPoint

QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RANaaS	RAN as a Service
RRM	Radio Resource Management
SDMA	Space Division Multiple Access
SDN	Software Defined Networks
SLA	Service Level Agreement
TDD	Time Division Duplexing
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
UE	User Equipment
veNB	virtual eNodeB
WDM	Wavelength Division Multiplexing
WLAN	Wireless Local Area Network
xDSL	DSL technologies

1 Executive summary

The second deliverable produced by iJOIN WP4 provides an explanation on how WP4 integrates in the general structure of the project, which is described in Section 2. iJOIN allows having different kinds of information flows associated to different functional splits traversing the transport network. This adds a new level of complexity and requires new solutions for the support of functionalities, e.g. mobility management, load balancing, routing or congestion control. Hence, WP4 provides enablers at network layer level to support the CTs that are being developed in WP2 and WP3. Section 2 also lists the main achievements of the WP4 activities, not only related to this deliverable elaboration, but also including other areas, such as contributions to standards and dissemination.

Section 3 describes how WP4 contributes to the support of the main iJOIN technical innovations. It further elaborates on the support of different functional splits between iSCs and RANaaS entities as well as the joint operation of the access and backhaul network layer in order to optimise the RAN system.

Section 4 provides a characterization, in terms of capacity, latency and other KPIs, of the transport network (backhaul) alternatives expected to support the iJOIN architecture. This is an input to other WPs and will be considered in the evaluation of their CTs, so the use of different transport technologies (optical, wireless, etc.) for supporting the proposed functional splits can be assessed.

Section 5 provides the complete description of the Candidate Technologies (CTs) that have been developed by WP4. These CTs provide solutions to technical issues posed by the iJOIN objectives that cannot be properly addressed with current architectural solutions (e.g., the existing LTE network architecture does not support in-session anchor mobility or load balancing taking into account backhaul load). They encompass five areas, namely distributed IP anchoring and mobility, network wide energy efficiency, joint path management and topology control, congestion and routing control, and network wide scheduling and load balancing. The description of each CT includes the scenario where they are expected to be applied, the adopted technical approach, and the proposed novel algorithms.

This set of CTs constitutes the basis of the functional architecture developed by WP4, which is described in Section 5.5.1. The proposed functional architecture is more than the addition of CTs, as it also includes conventional functional modules that are inherited from existing systems, as well as functionality which is required for the coordination and the implementation of the interactions of the modules. The defined functional architecture is based on the software defined networking architectural framework with a separation of the control and user plane, and with the centralisation of the control plane. Messages between the functional modules are described in order to facilitate the definition of OpenFlow protocol enhancements meeting future mobile network requirements.

The next WP4 deliverable, D4.3, will report on the evaluation of the different CTs. In Section 8, this deliverable provides a description of the evaluation methodology which will be applied in D4.3. It should be noticed that both simulations and proof of concept systems will be used for these purposes, depending on the CT characteristics. Section 8 also addresses the issue of compatibility between the different CTs in order to achieve the high level objectives defined for the project. Solutions for potential conflicts are provided.

In addition, Section 7 describes a cost analysis model in order to evaluate the economic viability of the iJOIN system with particular focus on heterogeneous backhaul technologies and applicability of functional splits. Detailed results of the application of this model will be reported in D4.3.

2 Introduction

WP4 activities are intended to develop network technical solutions allowing for the **support of different functional splits between iSCs and RANaaS entities**, as well as to **operate jointly the access and backhaul network layer** in order to optimise the RAN system. These are the main new key concepts proposed by the project. On top of this, WP4 has also proposed solutions in order to allow a more efficient operation of the network layer in terms of cost, energy consumption, mobility support, latency, etc. These activities have resulted in the definition of a set of Candidate Technologies (CTs) that will be described and specified in detail in this deliverable.

The network layer, in the context of WP4, is constituted by the set of elements that provide the connection from the termination of the radio interface at the iSC with the rest of the network, RANaaS or S/P-GW, with a certain service level. In traditional networks, the flows of information between the base station or remote radio head and the rest of the network are either the standard S1/X2 interfaces or the CPRI interface for Cloud RAN architecture. In the context of iJOIN, it is possible to have different kinds of information flows associated to different functional splits, which adds a new level of complexity and requires new solutions for the support of functionalities like mobility management, load balancing, routing, congestion control, etc.

In this sense, it is important to understand that WP4 role is not to develop technical solutions for the project key concepts indicated above (e.g., functional split of an existing distributed network-layer functionality), but to provide enablers to support the CTs that are being developed in both WP2 and WP3 in order to achieve them.

The definition of the WP4 CTs encompasses both the specification of the algorithms used to implement the functionalities to be supported, as well as the definition of the functional entities and the messages exchanged between them. The CTs are expected to meet the requirements identified in a set of relevant scenarios defined by WP5. A first description of the CTs was provided in D4.1 [5] and it is refined in the present deliverable.

One of the design principles adopted by WP4 for the definition of the CTs is the adoption of a software defined architecture, where the network control and forwarding functions are decoupled, enabling the network control to become directly programmable and the underlying infrastructure to be abstracted. This approach has been chosen because it is believed that it ensures that all the mechanisms are better integrated and cooperate more easily in order to achieve a joint overall optimisation of the performance. The WP has also explored the requirements that the support of the CTs with this architecture would pose on the OpenFlow protocol, one of the alternatives available for the implementation of Software Defined Networks (SDNs).

The potential benefits of CTs proposed will be evaluated for the scenarios defined by the project – the results of the evaluation process will be reported in deliverable D4.3, due at month M30. Some of the CTs will be evaluated in a test-bed that is being implemented in the context of WP6 activities. In this deliverable, however, the objectives and methodology used for this evaluation are described.

Then, the CTs should be integrated in the general architecture of the project. This activity is divided into two phases. In a first phase, integration of the WP4s CTs into a common architecture is performed, identifying commonalities in the functions each one implements, so they can be grouped, as well as potential interactions between functional entities of different CTs. However, it should be understood that the functional architecture proposed is more than the addition of the CTs proposed, as it also include conventional functional modules that are inherited from existing systems. The results of this phase are presented in this deliverable. In a second phase, the functional architecture is mapped into the network architecture developed by WP5. This would include interactions with functional entities of CTs developed by other WPs. This second phase is responsibility of WP5.

Key Contributions

The list below highlights the key contributions of this deliverable, as well as the main scientific advances of the technologies described in the deliverable, pointing out the main differences over the state of the art as well as the most significant results achieved (in terms of publications, patents, standardisation proposals, etc.).

- Final definition of the WP4 CTs: This document expands D4.1 [5] CTs description including additional information giving a final definition of each of the CTs.

- CT4.1 proposes a novel anchor selection and mobility management mechanism. The main goal of it is to select the optimal anchors for the user based on several aspects, such as: backhaul status, support for local breakout/offload, distributed anchoring, terminal/application specific aspects. The anchor selection is performed at flow bias enabling so fine-grained mobility management for each user. On the one hand the dynamic selection of the anchors allows for a better suited service for users, on the other hand it allows for an optimal utilisation of network resources. Most of the technical details and of preliminary result obtained by prototyping the CT4.1 on SDN Test-bed is novel for D4.2.
- CT 4.2 proposes a novel energy-efficient mechanism that considers not only the access but also the backhaul networks. In this document, starting from the theoretic analysis presented in D4.1 [5], we elaborate our heuristic mechanisms for access network. We discuss some qualitative and quantitative insights on some significant trades-off, and plan to extend the work to fully consider the backhaul network in D4.3. Finally, we present a novel mechanism that explores the potential energy-savings, even for short time-scale switching-off durations; this opportunity seems really advantageous for future and modern heterogeneous networks.
- CT4.3, Joint Path Management and Topology Control, investigates the fundamental problems of RANaaS positioning and dimensioning, i.e., answering the questions where to place RANaaS instances and how many resources to provide. This depends on the transport network structure, number of connected iSCs, data processing capabilities and side-constraints on latency and throughput, which result from the chosen functional split. CT4.3 provides a qualitative study on the different options where RANaaS instances can be placed and elaborates on pros and cons. Based on this study, an algorithm is proposed which is used to determine the optimal position and size under given side-constraints. Furthermore, CT4.3 provides a detailed overview of path-computation algorithms which are applicable to the iJOIN system.
- CT4.4 proposes a novel congestion control mechanism in order to allow the reuse of the same transport infrastructure to support information flows that have very different latency and capacity requirements as well as operational time scales. The mechanism is based on the use of a virtual queue with several configurable thresholds, as well as the use of a selective random packet dropping mechanism and a packet pacer required to solve potential incast issues. The support of the CT is expected to both improve the performance of the networks and contribute to their economic efficiency, as otherwise either a split-specific infrastructure should be deployed or an over-dimensioning of the network capacity should be assumed. Most of the technical details are new for D4.2.
- CT 4.5 proposes a novel load-balancing mechanism that considers not only the user perspective but also the network's perspective. As for the user perspective, one should consider QoE metrics such as the potential service delay or the blocking probability while distributing the load. On the other hand, regarding the network perspective, one should consider some network aspects as well, e.g., the equalisation of the loads between the network's elements. Thus, the support of this CT is expected to improve the performance of the network, by exploring the upcoming trades-off.
- From the scientific point of view, a major difference of the WP4 CTs over the state of the art is the SDN-centric view that has been adopted, which allows all the mechanisms to be better integrated between them and to cooperate more easily in order to achieve a joint overall optimisation of the performance.
- The description of the WP4 functional architecture has been further detailed, including extensive information on the interaction of the different WP4 modules. The specification of the functional architecture ensures that the whole WP4 system works consistently. While each designed CT covers an existing gap in current 3GPP LTE architectures, the integration of the new proposed iJOIN concepts in the functional architecture enables a seamless operation of the system.
- This document paves the way for the final stage of the project, which will be focused on the evaluation of the designed CTs. In order to do so, the evaluation objectives and methodology for each CT is carefully described in a standalone section. The evaluation results will be reported in D4.3.

- A fundamental problem, analysed in this document, is the placement of the RANaaS platform inside the EPC network and how to associate each RANaaS with a particular set of iJOIN Small Cells (iSC). An analysis of this issue is included in this deliverable, resulting from the collaboration with WP2 and WP3. This work has been done under the framework of CT 4.3.
- An analysis of the way WP4 developed technologies help to achieve the main iJOIN objectives is explained in a devoted section at the beginning of this deliverable. The goal of this section is to clearly scope how WP4 work relates to the key iJOIN characteristics. As an example, we analyse the implications of using an SDN-focused architecture. Considerations on the potential impact to the recently established Wireless & Mobile Working Group (WMWG) at the ONF have been included as well.
- The standardisation work has continued, achieving significant impact in the IETF [9][10]. Within the DMM WG, the two principal documents (and the only ones at the time of writing of this deliverable) are co-authored by iJOIN participants. Another WG document describes the applicability of congestion exposure mechanisms for EPS-based mobility based architectures within the CONEX WG [11]. Additionally, work at the ONF has continued, pushing some of the iJOIN concepts.
- A paper describing the advantages and challenges of adopting an SDN-based approach in a mobile network has been published in the IEEE Wireless Communications Magazine, Special Issue on Special Issue on “Research & Standards: Leading the Evolution of Telecom Network Architectures” [6]. This paper was selected as the feature article of the journal issue, and also as the free COMSOC article of the month.
- A paper describing a DMM solution, from which some of the technical approaches of CT4.1 are derived from, has been accepted to IEEE Transactions on Mobile Computing [7].
- A paper comparing different DMM approaches, including one based on the SDN approach followed in iJOIN, has been accepted for publication in IEEE Communication Magazine (special issue on Recent Advances in Technologies for Extremely Dense Wireless Networks) [8].
- The publication “An Analysis of Backhaul Costs of Radio Access Networks using Stochastic Geometry” has been accepted at ICC 2014.
- The Open Source DMM platform (http://www.odmm.net/) has been released.
- A CT4.1 demo was carried out in EuCNC 2014 in Bologna.

3 Key concepts

WP4 does not investigate on how to perform functional split on network layer mechanisms, but rather focuses on network-wide enablers for the efficient support of the functional split CTs developed by WP2 and WP3, and also on joint RAN/BH optimisation approaches. This section explains how WP4 support both key concepts within the iJOIN system concept.

3.1 Functional Split

One of the cornerstones of the iJOIN project is the support of the flexible functional split by means of the RANaaS infrastructure, which allows for the execution of radio interface functionalities with different levels of centralisation. The concept of flexible functional split is illustrated in Figure 3-1.

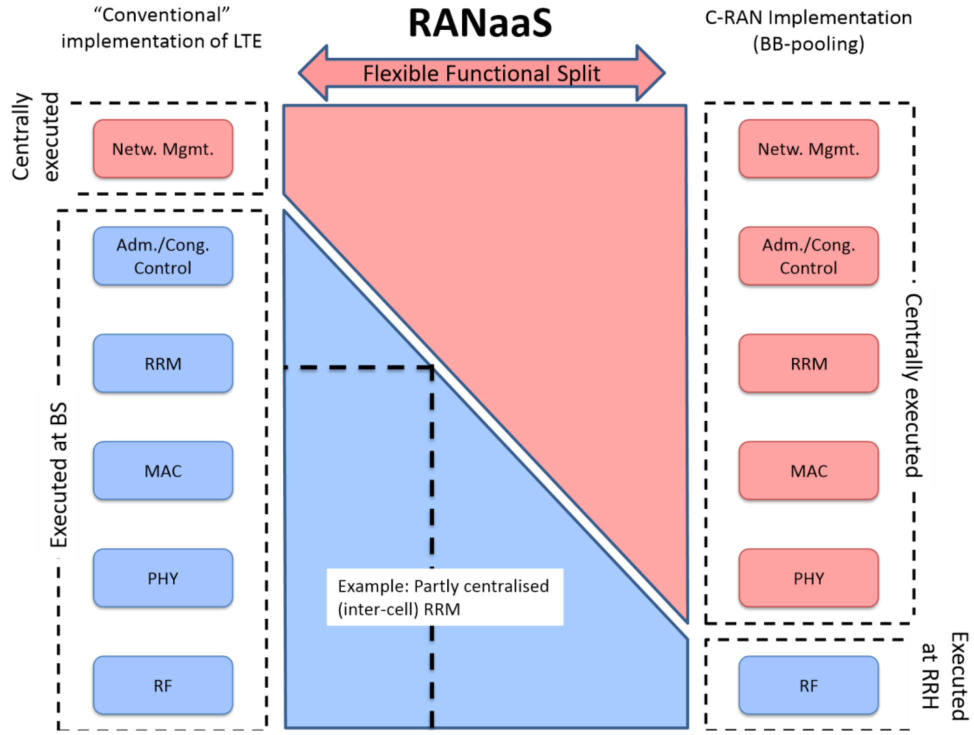


Figure 3-1 Illustration of the flexible functional split implementation through RANaaS

In RANaaS, those radio access network (RAN) functionalities that are centralised are implemented through virtualisation on a cloud-infrastructure. The support of the flexible functional split provided by RANaaS has significant implications for the network layer:

- Different functional splits result in different requirements on the transport infrastructure that connects centralised and distributed functionalities. Minimum required capacity and latency may significantly differ depending on the chosen functional split. The possibility of supporting flows associated to different functional splits over the same infrastructure requires the development of network layer solutions. This aspect has heavily influenced the design decision adopted in WP4 of following a Software Defined Networking (SDN) approach. It allows to better use the network capacity as well as to react more timely to changes, e.g., due to load or energy optimisations.
- The implementation of the RANaaS concept allows for the support of virtual eNodeBs, which may have implications on the support of network layer functionalities, e.g.:
    - Network layer energy optimisation algorithms (CT4.2) have to consider the impact that switching off a particular iSC might have on CoMP mechanisms.
    - CoMP requirements (from WP2) have to be considered when computing paths between the iSC and the assigned RANaaS for a given functional split.
    - The concept of veNB must be considered when taking mobility decisions, as a change of iSC might imply a change of veNB. Changing veNB implies additional mobility signalling mechanisms as compared to mobility within the same veNB.

- The RANaaS concept opens the possibility of supporting new network sharing schemes as well as the support of multi-tenancy. In particular, a given backhaul network and even the physical radio part (iSCs) can be shared by different operators, which could deploy separate RANaaS instances. In order to do so, traffic from each operator would need to be routed in the backhaul towards the appropriate RANaaS, meeting the associated QoS constraints. Additionally, different functional splits might be applied by the different RANaaS instances.
- The adoption of the software defined architecture implies a new way of supporting network layer functionalities such as mobility and load balancing.

As it can be seen, even though WP4 CTs do not directly implement a functional split, they are required in order to enable the different functional splits performed by WP2 and WP3 CTs. Besides, WP4 CTs considers in its design the potential impact posed by the specific characteristics of WP2 and WP3 CTs.

3.2 Joint Backhaul Access design

It is a likely assumption that small cell deployments will be connected by heterogeneous backhaul technologies consisting of fibre, microwave and high frequency wireless solutions. Most radio access designs consider that the backhaul network is sufficiently dimensioned or even over-provisioned. This is an assumption that will be challenged when the access network moves towards a higher capillarity, due to the massive use of small cells, and a more centralised operation.

Hence, it seems clear that potential limitations of the backhaul must be considered when operating the radio access network, e.g., resource availability, supported latency, potential costs when transport services are provided by a third party. This helps potentially to optimise the overall system performance and to reduce costs. These limitations are more relevant for the case of using wireless backhaul technologies as its resources are limited and more prone to instability effects. The introduction of the flexible functional split supported by RANaaS adds an additional complexity because different functional splits will have different requirements. Section 4 characterises several backhaul technologies in terms of latency and bandwidth. Both are relevant parameters to consider when computing the paths used for the traffic between the iSC and the RANaaS, and to assess if a given functional split is feasible.

Within WP4, the main technical enabler for the support of a joint operation of backhaul and access is the use of the architectural concepts associated to Software Defined Networking (SDN). The SDN concept is based on the separation of the control plane from the data plane within the network, allowing the intelligence and state of the network to be managed centrally while abstracting the complexity of the underlying physical network. The Open Networking Foundation (ONF) is taking the lead in SDN standardisation, and has originally defined an SDN architecture model. However, it is important to highlight that the iJOIN approach goes beyond what is being proposed today for the use of SDN in the mobile backhaul network. SDN is considered an enabler for taking better transport decisions at each point in the network and it is based on the use of network elements with the capability to report and act dynamically in response to changing conditions. In the context of the proposed iJOIN architecture, the controller supports new functionalities that clearly exceed the actual capabilities of the protocols used by these networks so far.

It is important to notice that ONF opened a new working group, Wireless & Mobile Working Group (WMWG), which is chartered to collect use cases and determine architectural and protocol requirements for extending ONF based technologies towards wireless and mobile domains (iJOIN concepts has been contributed to this group). Areas of interest include optimisation and management of various network types including wireless backhaul, cellular Evolved Packet Core (EPC) — which entails traffic management, traffic steering, and network security —, IEEE technologies such as OmniRAN, and unified access and management across enterprise wireless and fixed networks (e.g., campus Wi-Fi).

However, the joint operation of the access and the backhaul imposes specific requirements from the network layer point of view, e.g., the activation of load balancing or mobility procedures due to lack of resources not in the radio access but on the backhaul network. One particular and very relevant example of joint access and backhaul network design in WP4 is CT4.2: energy optimisation. Algorithms developed within CT4.2 decide whether to turn on/off a network node, thereby considering jointly access network aspects (e.g., coverage, load, veNB structure, etc.) and backhaul aspects (e.g., network load, location of associated RANaaS entities, etc.).

4 Backhaul network settings

One of the key pillars of the iJOIN project is the concept of flexible functional split, which allows for centralising RAN functionality in very dense small cells interconnected via heterogeneous backhaul networks. As it has indicated before, the role of WP4 is not to investigate any functional split alternatives, which have been defined as CTs by WP2 and WP3, but to provide the network level enablers to make them feasible. However, in order to asses this feasibility, it is important to ensure that the transport network used provides the required performance in terms of capacity, latency, etc., to support a given functional split in a given operational scenario. This section is thus intended to address this issue.

The project has defined four common scenarios (CS), introduced in D5.1 [25], which represent different realistic scenarios of an iJOIN deployment. Depending on the scenario, several backhaul technologies might be considered. This section resumes common reference parameters defined in iJOIN WP4 for the assessment of CTs related to the performance in the transport network.

A generic backhaul scenario considered by iJOIN is shown in Figure 4-1. We consider both wired and wireless links for the interconnection of small cells with the metro network. Different deployment options are possible, depending on the scenario. For example, iSCs might be connected via wireless links to one iJOIN transport node and from there with fibre or cable based Ethernet to the aggregation network, or even a multi-hop wireless network might be used to provide connectivity to the aggregation or metro network. In order to be able to perform a characterisation of the latency and bandwidth characteristics of a given deployment scenario, it is important to study the latency and bandwidth characteristics of several access technologies that can be potentially used in the backhaul network. This information is important to assess the performance of the different CTs and also to evaluate under which situations each of the different iJOIN innovations provides a significant improvement.

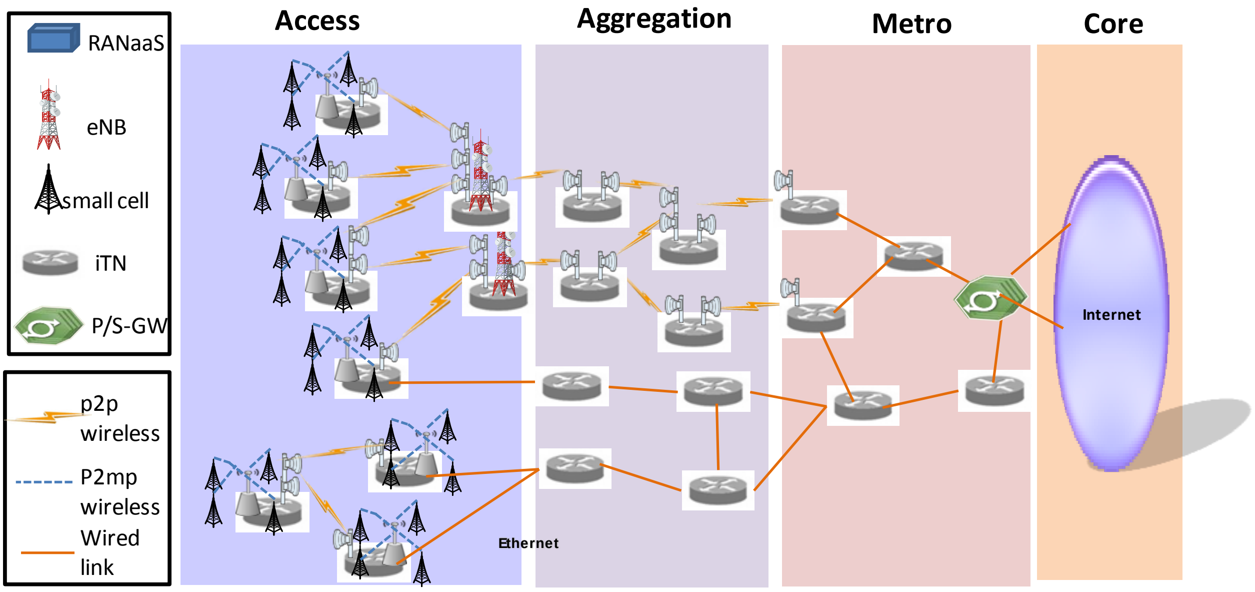


Figure 4-1: iJOIN generic backhaul scenario

In Table 4-1, we characterise and classify the different network technologies that we believe are feasible to be used in a given backhaul network deployment. This table is used as a reference by the iJOIN CTs to assess if a given functional split or optimisation feature is feasible under a particular common scenario or deployment realisation.

Latency requirements need to be fulfilled by the backhaul for reliable operations in RAN as well as to enable different functional split options in the RANaaS. 3GPP defines a number of 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 1ms sub-frame granularity. At the MAC layer, the HARQ timing is the most critical one. Once a sub-frame has been sent at sub-frame *n* for a given HARQ process, an acknowledgement (positive or negative) is expected at sub-frame *n*+4. Due to the synchronous nature of HARQ in the uplink, any functional split at the base station MAC layer requires the round-time trip time plus the processing to be done in 3ms. Having this in mind, it seems that wireless backhauling could only be used in some limited scenarios and only with specific technologies because, for instance, involving multiple hops might not be feasible.

On top of these constraints, iJOIN CTs are characterised by further latency requirements to be met in order to successfully operate. WP2 CTs are mainly characterised by very tight constraints (from below 1ms to few ms), i.e., to exchange up-to-date CSI for coordinated inter-cell interference management or user messages for centralised or distributed signal reception. In WP3, iJOIN CTs are characterised by a larger range of latency requirements: CTs focusing on very fast radio resource management have latency constraints below 1ms while coarse grained RRM mechanisms operate on a time scale larger than a LTE time frame (10ms). Finally, mechanisms that focus on the RRC and BH optimisation have light latency constraints (around 1s). WP4 CTs do not impose critical constraints on the backhaul latency and bandwidth. They can be rather considered as part of the enablers of the functional split concept, aiming at ensuring a certain connectivity characteristics in the backhaul between the iJOIN small cells and the RANaaS.

Table 4-1: Backhaul Classification [24]

Number	BH technology		Latency (per hop, RTT)	Throughput	Topology	Duplexing	Multiplexing Technology
1a	Millimeter wave	60GHz Unlicensed	≤5 ms	≤800 Mbit/s	PtP (LOS)	TDD	--
1b			≤200 µsec	≤1Gbps	PtP (LOS)	FDD	--
1c		70-80GHz Light licensed	≤200 µsec	≤2.5 Gbit/s	PtP (LOS)	FDD	--
2a	Microwave (28-42 GHz) Licensed		≤200 µsec	≤1Gbps	PtP (LOS)	FDD	--
2b			≤10 ms	≤1Gbps	PtmP (LOS)	TDD	TDMA
3a	Sub-6 GHz Unlicensed or licensed		≤5 ms	≤500Mbps	PtP (NLoS)	TDD	--
3b			≤10 ms	≤500Mbps (shared among clients)	PtmP (NLoS)	TDD	TDMA
3c			≤5 ms	≤1 Gbit/s (per client)	PtmP (NLoS)	TDD	SDMA
4a	Dark Fibre		5 µs/km × 2	≤10 Gbps	PtP		--
4b	CWDM		5 µs/km × 2	≤10·N Gbps (with N≤8)	Ring		WDM
4c	Metro Optical Network		250 µs	≤1 Gbps	Mesh/Ring		Statistical Packet Multiplexing
4d	PON		≤1 ms	100M – 2.5Gbps	PtmP		TDM (DL)/ TDMA (UL)
5	xDSL		5-35 ms	10M – 100Mbps	PtP		--

Table 4-1 lists relevant backhaul technologies and provides an overview of latency and throughput performance. The following assumptions have been applied to derive Table 4-1:

- The latency of wireless BH techniques (1a-3c) is affected by the duplexing technique (TDD/FDD) and, in the PtmP case, by the multiple access technique (e.g. TDMA). In general the FDD duplexing introduces the minimum latency. The TDD technique introduces a larger latency that depends on the frame length. The latency is related to the availability of a time slot when the packet arrives in the transmission buffer. The TDD increases also the latency jitter for the reason said before.
- Concerning 1a (Millimetre wave) the products in the 60GHz band typically adopt the TDD duplexing in order to have a balanced attenuation for DL and UL. The 60 GHz band, denoted as V-BAND in located in the absorption peak of the oxygen (O_2). The typical channel bandwidth for 1a) is

200 MHz. The maximum range for 60 GHz millimetre wave is typically 500 m (using directional antennas).

- Concerning 1b (Millimetre wave) the products in the 70-80 GHz band (E-BAND) typically adopt FDD duplexing. This is the reason of the lower latency compared to 60 GHz. The typical channel bandwidth for 1b) in 70-80 GHz band is 250 MHz $\times$ N (with N$\leq$4). At present there is a limited availability of commercial products operating in the 70-80 GHz band designed with specific characteristics for small cell backhaul (i.e. low power, small antenna size and auto tracking). The maximum range for 70-80 GHz millimetre wave is typically 3 km (using directional antennas).
- The throughput values for 1a/1b (Millimetre wave) for both 60GHz and 70-80 GHz are based on the equipment commercially available today.
- The introduction of the so called Wireless CPRI, proposed by some vendors, in wireless backhaul solutions introduces a limitation in the adoption of the AMC (Adaptive Modulation and Coding) which may reduce the availability of the link.
- Concerning 2a/2b (Millimetre wave), it seems reasonable to consider frequencies above 28 GHz. Assuming in fact that the maximum range for the backhaul of a small cell is in the order of 1 km, the use of higher frequencies facilitates the spatial reuse of the available frequencies and also brings advantages in terms of compactness of the equipment. There are different options for the channel bandwidth of 2a/2b, with a maximum of 56MHz.
- Concerning 3a/3b/3c (Sub 6GHz solutions), these solutions adopt typically OFDM. In particular the item 3c refers to advanced Sub 6GHz solutions that may adopt beam-forming (i.e., SDMA as multiple access technique) that could be available in the near future on the market. The usage of SDMA compared to TDMA may bring a reduction in the latency. There are different options for the channel bandwidth of 3a/3b/3c, with typical values ranging from 5 to 40MHz.
- Option 4a, which implies the leasing of unlit fibre cables (or wavelengths), transceivers should be provided at the edges of the fibre.
- Concerning 4c (Metro Optical) the statistical multiplexing is used (while it is not used for 4a and 4b being basically PtP or ring solutions).
- Concerning 4d (PON) the latency depends on the type of container that is assigned to the upstream traffic. Assuming that a container TCONT Type 1 is assigned, which has reserved bandwidth, a RTT of 1ms seems feasible for GPON. In general the latency is not symmetrical between downstream and upstream due to the different multiple access techniques (TDM for downstream and TDMA for upstream). In particular the link that mainly affects the latency is the upstream, where the one way latency may increase to several ms if a container with a lower QoS level is assigned.
- Concerning 5 (xDSL) the upper limit of the latency should be increased to 35ms (in particular it applies for the VDSL2 case @100Mbps which is the most suitable for small cell backhaul). In general the latency depends on the synchronization speed (especially for the lower rates) and on the interleaving configuration used as protection against impulse noise.

5 CT Description

In this section, we describe in detail each of the network-layer CTs. These CTs are based on the preliminary descriptions in D4.1 and provide a complete definition of each of the designed mechanisms, which will be evaluated in D4.3. Details of the evaluation methodology are described in Section 8.

The reader should take notice that in the description of some of the CTs, some references are made to the modules of the functional architecture that will be detailed in Section 5.5.1. This functional architecture was already been introduced in D4.1 [5] and D5.1 [25].

5.1 CT4.1: Distributed IP Anchoring and Mobility Management

5.1.1 Scenario

This CT is about Anchor Selection and Management to support mobility. The main goal of Anchor Selection is to select the optimal anchor for the user via which the traffic is routed outside the mobile network, based on several aspects, such as: backhaul status, support for local breakout/offload, distributed anchoring, terminal/application specific aspects. The anchor can be the PGW, a veNB, an iTN, or an iLGW (the latter three iJOIN specific network elements are introduced in D5.1 [25]). The anchor selection in the CT proposed is performed at flow level. For example, a different anchor may be selected for new flows when an UE moves maintaining old flows anchored to the previous anchor. The following figure shows a scenario where four different anchors are selected for four different flows for a given UE.

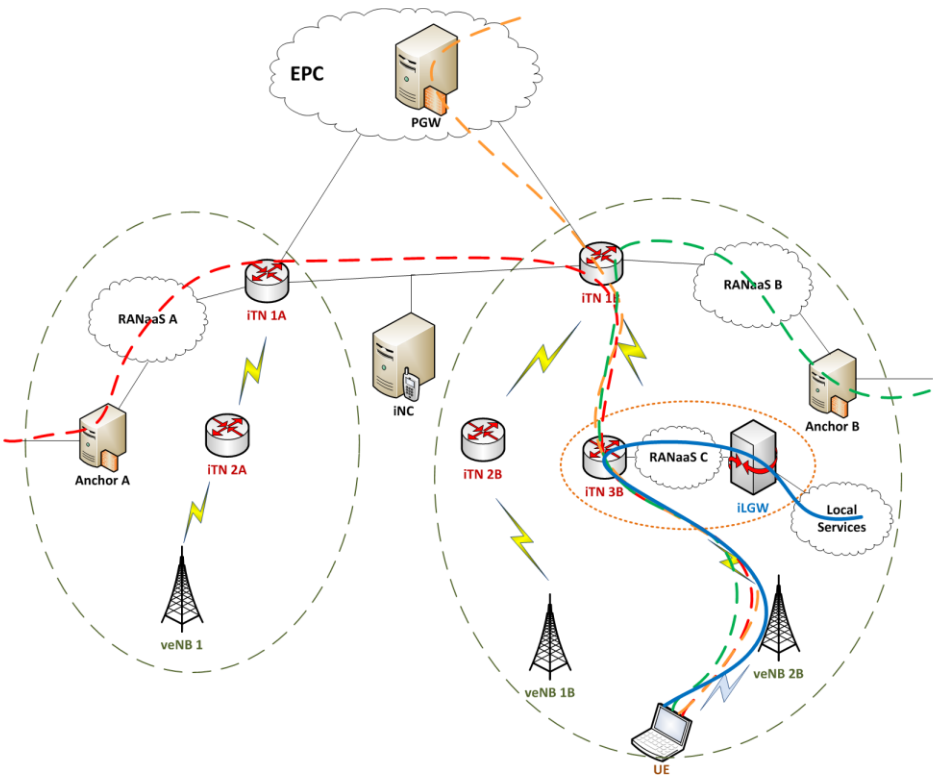


Figure 5-1 AMM: Anchor selection for different flows

The dynamic selection of the anchor allows for an optimal utilisation of network resources. Thus, the main goal of Mobility Management is to select the best anchor and to configure properly the network in order to enable mobility support for the targeted flows. Note that this selection considers aspects as the backhaul status and the RANaaS placement, which are critical in the overall iJOIN vision. The integrated approach aims also to achieve a fast and seamless user experience keeping the anchors closer to the UE.

In the designed solution, both the iTN and veNBs play a key role in order to perform fast handovers without requiring high signalling exchange to the core network. A key feature of this proposal is the provision of distributed traffic forwarding between the involved veNBs/iTNs in a way that the user will not experience any loss of service or any performance degradation during this process.

5.1.2 Approach

The approach proposed for this solution is based on the interaction of different modules. Indeed, the mobility solution is not a standalone solution and an interaction with other modules is required since the goal of this CT is to select the best anchors for the UEs. Selecting the anchor for the UE is not enough for correctly steering the UE's data traffic and a path reconfiguration in the network is required. In order to achieve mobility the required interaction is described in the following paragraph.

Interaction between CT4.1 and CT4.3

As stated above, CT4.1 does not provide any mechanism for reconfiguring the paths in the network. Hence, CT4.1 and CT4.3 are integrated and interact to provide mobility in a jointly fashion. In order to explain the interaction between the two CTs, we introduce now some concepts about the functional architecture followed by WP4. The full description of the functional architecture can be found in Section 5.5.1. Each CT defines a set of modules which interact with the other modules in order to accomplish a specific task. These modules run on the iJOIN Network Controller and follow an SDN-paradigm. The AMM module is the module associated to CT4.1 and it is in charge of managing the mobility of the UEs attached to the network. When an UE moves from a point of attachment to another, AMM runs different algorithms to select the optimal anchors. After this step, AMM interacts with the module defined by CT4.3, namely TEEM, which is in charge of computing and configuring the paths in the network. The interaction between AMM and TEEM will be detailed in Section 6. For better understanding the interaction between the modules, we show the 3 cases considered by the CT4.1: Initial UE attachment, Intra anchor UE mobility and Inter anchor UE mobility.

Initial UE attachment

Figure 5-2 shows the signalling chart for this scenario, the communication between the TEEM module and AMM module is marked in red. Upon the initial UE attachment, the AMM computes a prioritised list of anchors, following the algorithm described in D4.1. Once a list of anchors has been selected, the AMM proceeds to trigger the TEEM event requiring the establishment of new paths. The AMM provides to the TEEM the veNB to which the UE is connected, the list of selected anchors and the list of selected gateways. At this point TEEM checks if it is possible to set-up a path between the veNB and the gateway to the selected anchor, starting for the most preferred anchor. During the other phases of the procedure there is no communication between the two modules. Note there is an interaction between the iNC and the core network (the MME) via the J4 interface.

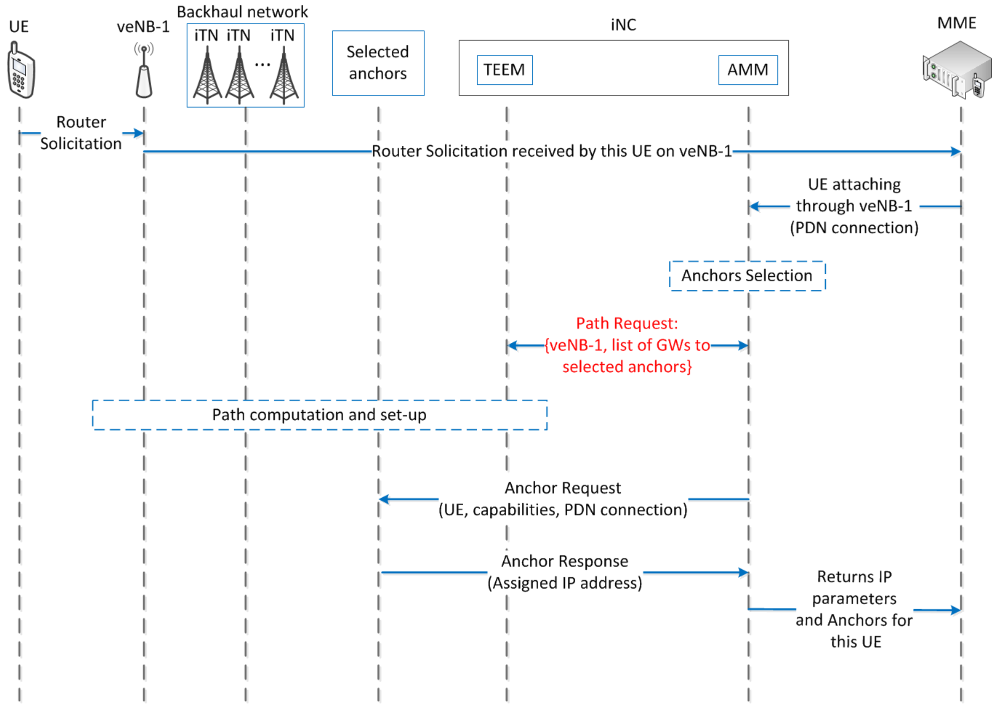


Figure 5-2 AMM and TEEM interaction initial UE scenario

Intra anchor UE mobility

In Figure 5-3 it is reported the signalling chart for this scenario, the communication between the TEEM module and AMM module is marked in red. When the UE moves from a veNB to another, the AMM evaluates whether a new anchor assignment is necessary (just considering mobility and application requirements). In this case, no change is required, which means that the same anchor is provided back as the most preferred one. Since the veNB serving the UE has changed, the AMM needs to contact the TEEM module so the forwarding path is updated in the backhaul and RAN. The AMM provides to the TEEM the new veNB to which the UE is connected, the selected anchor and the selected gateway. During the other phases of the procedure there is no communication between the two modules. This case is a clear example of CT integration. Indeed, the UE mobility could not be achieved without the cooperation of AMM and TEEM.

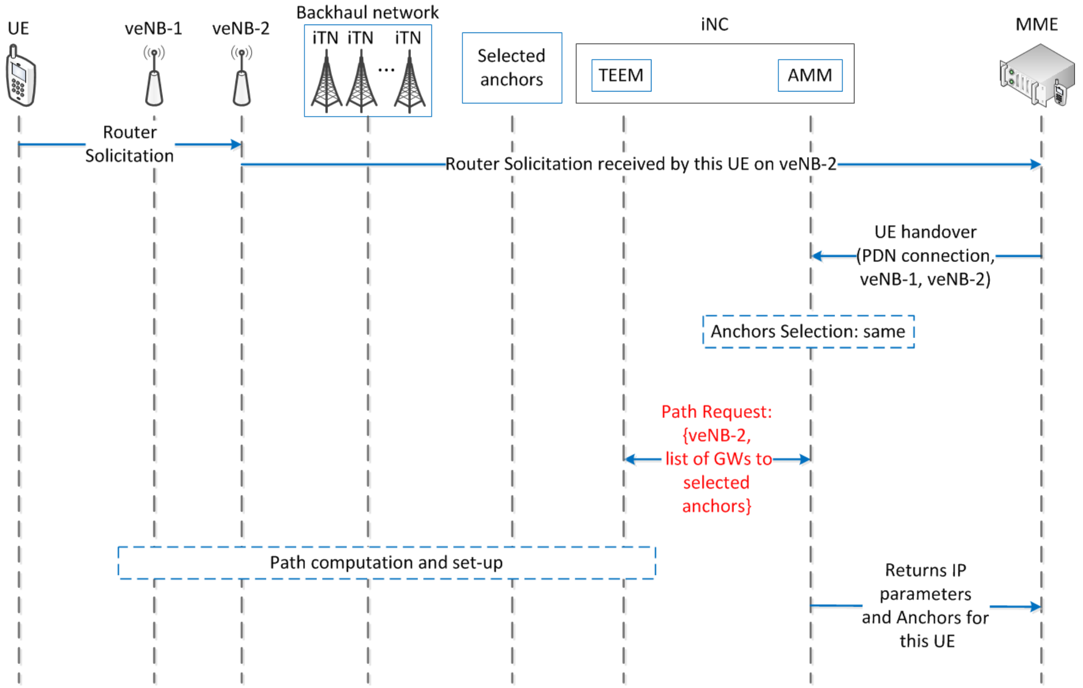


Figure 5-3 AMM and TEEM interaction in intra-anchor mobility scenario

Inter anchor UE mobility

In Figure 5-4 it is reported the signalling chart for this scenario, the communication between the TEEM module and AMM module is marked in red. When the UE moves from a veNB to another, the AMM evaluates whether a new anchor assignment is necessary (just considering mobility and application requirements). In this example, a different anchor is selected (for example because the new veNB has local-breakout capabilities). The AMM communicates with the TEEM in two steps:

1. The AMM provides to the TEEM the new veNB to which the UE is connected, the selected new anchors and the selected gateways for new anchors. In this step the AMM requires to the TEEM to compute a path for the path between the new veNB and the new selected anchor.
2. The AMM provides to the TEEM the old veNB to which the UE was connected. In this step the AMM requires to the TEEM to compute a path for the path between the new anchor and the old anchor.

During the other phases of the procedure there is no communication between the two modules.

The scenarios afore described show the integration required by AMM and TEEM modules in order to provide mobility to the UE. We also described as the event-driven paradigm suits very well for this kind of integration bringing many advantages. Finally, we described as well how the use of this paradigm can benefit in case of service oriented systems such as the iJOIN functional architecture.

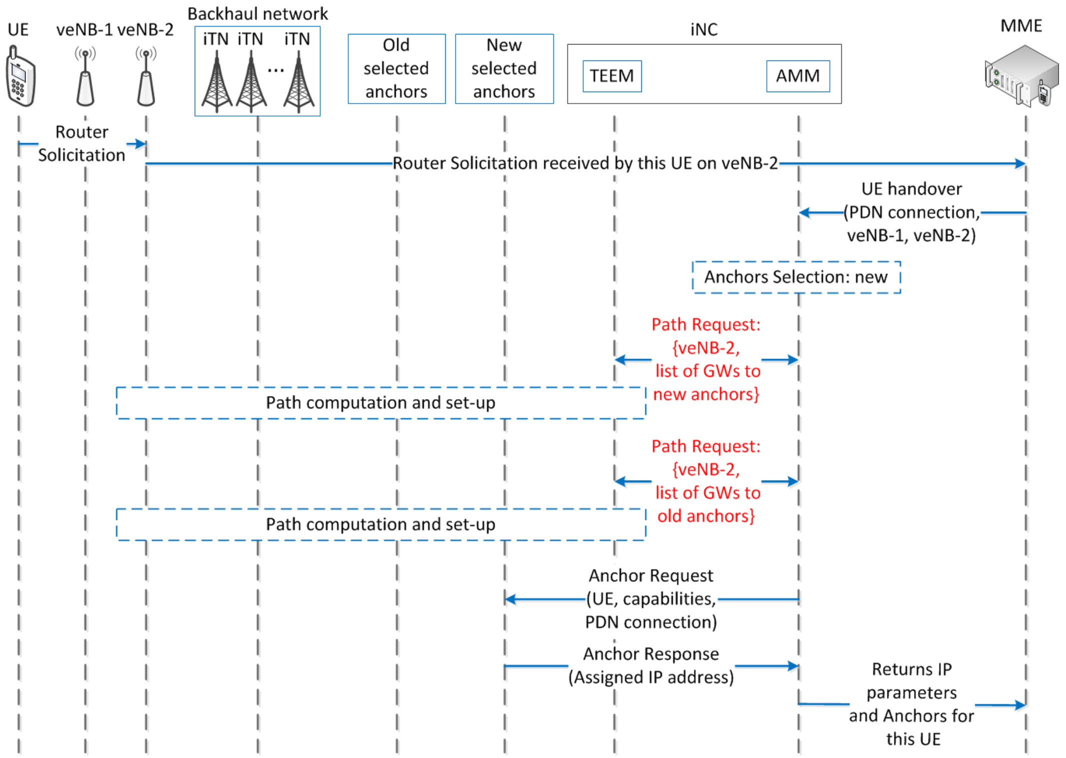


Figure 5-4 AMM and TEEM interaction in inter-anchor mobility scenario

5.2 CT4.2: Network Wide Energy Optimisation

5.2.1 Scenario

Energy efficiency is both ecologically and commercially important to Information and Communication Technologies. Indeed, 70% of the BS energy consumption is caused by power amplifiers and air conditioning, which are used to keep the cell active even when there is no traffic in the cell. Hence, the optimisation of utilisation of the iSCs is considered in this CT, which may have a large impact on the overall cellular energy efficiency. Two algorithms are proposed, upon a common architectural environment, for achieving energy savings. Furthermore an enhanced scheme is considered to improve performance in terms of system energy consumption. In this enhanced scheme we investigate the benefit of employing adaptive CoMP clustering for enhancing switch on/off operation of access and backhaul nodes. The main concept is to adaptively form CoMP clusters so as to improve overall system performance such as network coverage. In that way, underutilised iSCs (and potentially iTNs) will be able to switch-off more often and for longer time periods as users in these cells will be able to achieve their QoS constraints with higher probability. Note that adaptation will be performed in terms of *i)* which and when iSCs cooperate, as well as, *ii)* the transmit power used by each iSC. Allowing iSCs to also adapt their transmit power according to their cell load, rather than switching off and on too often, will avoid bringing too much oscillatory energy consumption. Adaptive CoMP clustering is expected to bring extra energy efficiency gains by enhancing switch on/off operations, however, extra system energy consumption will also be introduced from higher backhauling and processing capabilities required to employ such scheme. In order to investigate this tradeoff and translate any energy gains into a system level, we will also introduce a holistic system energy consumption model tailored specifically for iJOIN architecture.

WP4 functional architecture is introduced in D4.1. There are several components (AMM, NEO, RAC, TEEM, MM and NMM) that are associated with the iNC, the key network entity in charge of configuring, monitoring and driving the operation of the rest of the RAN and backhaul network entities. The NEO module, defined in Deliverable D4.1, that is associated with the Network Wide Energy Optimisation CT, monitors the network status and load, and runs different algorithms to optimise the overall energy consumption while ensuring that the network wide performance is not compromised. The module is in charge of taking network wide decisions about switching on/off physical nodes, as well as ensuring that UE traffic is still properly routed by the nodes that are running at each time. Thus, the objective is to minimise the energy consumption of the cellular network, by minimising the energy that its nodes consume. For now we consider switching-off schemes for iSCs, and we present some preliminary results. In the next deliverable, we are going to include also the final result including sleeping modes for iTNs.

Thus, in our approach, we try to decrease the energy consumption of the cellular network, by switching-off some BSs, subject to some QoS constraints. Thus, we try to minimise the energy required for the cellular network, by minimising the energy consumed by the BSs, if we switch some of them off; while at the same time taking care of the users' QoS. Indeed, the more the BSs we turn off, the larger the traffic that the BSs that remain ON have to deal with, so the fewer the resources left for each served user. Our goal is to switch-off some BSs by maintaining the resources above some threshold that satisfy the minimum demanded QoS. Furthermore, at the proposed enhanced scheme considering adaptive CoMP clustering we target to decrease the energy consumption of the whole system and exploit the low-energy-consuming processing capability of the RANaaS platform to enhance switch on/off operations in the system. Thus, UEs served by underutilised iSCs may be handed over to CoMP clusters (formed by multiple neighbouring iSCs) so that iSCs can switch-off for decreasing overall system energy consumption as long as the system QoS constraints are ensured to be met.

5.2.2 Approach

Most past studies are performed in the context of large macrocells under homogeneous traffic profiles, and with large time-scales (e.g., turning off BSs during the night [2]). Furthermore, usually simple QoS requirements are considered when applying such techniques, e.g., signal quality as in [3], or traditional blocking probabilities as in [4]. In modern and future cellular networks, dealing with energy consumption issues becomes more challenging. Significantly more opportunities arise for switching off BSs in smaller time scales (e.g., in the order of some minutes), due to (a) coverage overlaps stemming from heterogeneous and/or independent deployment of cells, (b) larger spatio-temporal load variations due to the smaller number of users associated to each cell, and (c) power-proportional and load-dependent BS. Yet, exploiting such opportunities must be done without violating agreed QoS performance for users. The evaluation of the latter is a rather daunting task, due to the diversity of user traffic (streaming, voice, web, file download, etc.) and service and performance guarantees offered to users. As a result, a number of interesting questions arise: which QoS metric(s) should be used in such future SCNs? Which types of users and BSs should one consider when making a power management decision? Should the duration of switching-off period affect our decision, and if so, how?

Moreover, the comparison will include benchmarks from the state-of-the-art literature in Network-wide energy efficiency for small cells. More specifically, we will compare our work with both optimal and heuristic energy efficiency solutions which are applicable to 3GPP LTE small cells. In this effort, different types of mechanisms, i.e. semi-centralised and de-centralised will be compared taking into account factors like the computational complexity and the signalling load as the size of the network increases.

Towards answering the above questions, we identify three QoS constraints related to different ways that the performance of a User Equipment (UE) could deteriorate. We then derive analytically the probability of violating each of them as a function of user and network parameters and planned switch-off duration. Specifically, we consider:

- **Network coverage**, i.e., the probability that a random user experiences poor signal quality when he/she needs to use the network (e.g., making a call, or sending a web request), defined as failure probability. While switching-off an iSC, then some users are going to be attached to further iSC, so the average failure probability of a random user increases. We denote as $p_{failure}$ the maximum tolerant failure probability, defined from the operator. An example, of a violation for this constraint is depicted in the following figure. More precisely, if we switch-off the left BS, the user with low-signal quality will have to deal with low-signal related problems with high probability, in case he tries to use the network afterwards. Our first constraint expresses the metric of this probability.

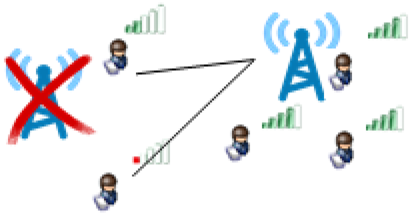


Figure 5-5 Coverage Constraint

- **Admission control and "blocking" probabilities** *(for GBR flows that require a "dedicated" amount of bandwidth)*; these probabilities are not only related to user admission but also admission of flows that require a certain amount of dedicated bandwidth. While switching-off a iSC, then some users are going to be attached to further iSCs, so some iSCs will have to deal with more flows that require a certain amount of bandwidth, thus the blocking probability of such a flow due to lack of resources increases. We denote as p_{block} the maximum tolerant probability that is defined from the operator. An example of a violation for this constraint is depicted in the Figure 5-6. More precisely, if we switch-off the left BS, the (remote) BS on the right will have to deal with increased demand-rate, and potentially with more bandwidth-hungry users (since the handed over users are located in further locations, so they are more demanding). Thus, this constraint considers the probability that an average flow of the remote BSs will be blocked due to lack of resources.

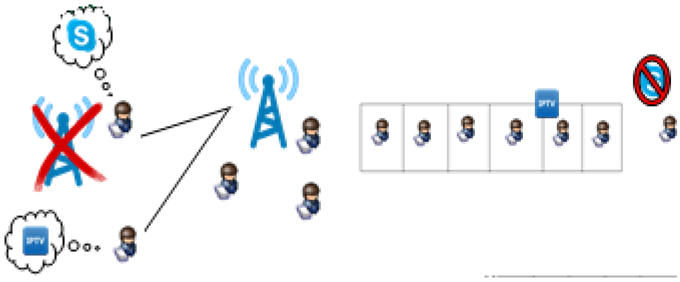


Figure 5-6 Blocking Probability Constraint

- **Service delay** *(for non-GBR "best-effort" flows);* and the probability of delay exceeding some desired upper bound. While switching-off an iSC, then some users are going to be attached to further iSCs, so some iSCs will have to deal with more best-effort flows, thus the ongoing delay of these flows increases. We denote as D_{max} the maximum delay threshold that is defined from the operator. An example of a violation for this constraint is depicted in the following Figure. More precisely, if we switch-off the left BS, the (remote) BS on the right will have to deal with increased demand-rate, and potentially with more bandwidth-hungry users. Thus, the average resources for each user are decreased. Overall, this constraint considers the service delay of an average best-effort flow.

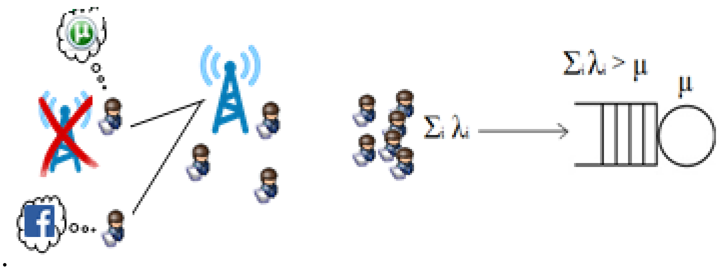


Figure 5-7 Service Delay Constraint

Thus, our decision for switching-off an iSC, will take into account the three of the above QoS constraints: if no one of them is going to be violated (with respect to the thresholds defined from the operator) with a potential switching-off iSC, then we are allowed to switch-off the considered iSC. Thus, we have to check each one of the iSC, so at the end of the day we will have switched-off as much iSC as possible, and at the same time users will not experience any "confusing" situations related to their QoS, such as deep-fading while experiencing a call.

Obviously, the larger the QoS thresholds ($p_{failure}$, p_{block}, D_{max}) defined from the operator, the less strict we are with the switching-off criteria, so the more iSC we can switch-off and the more energy we can save. Our framework, considers the above constraints even for short switching-off periods. Thus, we are able to find the potential energy savings even for a switching-off period in the order of some minutes.

CoMP-enhanced Scheme

For the enhanced scheme we examine an efficient way to employ CoMP Joint Transmission (JT) taking into account the tradeoff between the extra energy savings originating from enhanced switch-off operations and the extra energy consumption due to adaptive CoMP clustering. In general, extra energy savings are expected to be realized due to three factors:

1. iSCs can be switched off more often and for longer periods;
2. Backhaul links and iTNs can also be switched off more often and for longer periods and;
3. iSCs can adapt their Tx power to lower levels (i.e., cell breathing) when QoS constraints are overly satisfied

On the other hand, extra energy consumption originates from two major factors:

1. due to extra data processing needs and;
2. due to extra needs for data transport through the backhaul;

Figure 5-8 illustrates an example scenario to comprehend where the benefit from the proposed approach can come from. In this scenario an underutilised iSCs and two neighbouring iSCs are depicted. By employing the conventional switch on/off scheme, the underutilised iSC will be able to be switched off and save energy rarely and for shorts periods of time. In some cases, i.e. when its served users cannot reach their QoS constraints when handed over to the next-best neighbouring iSC, the underutilised iSC may not be able to be switched off at all. On the other hand, through the CoMP-enhanced scheme the UE QoS probabilities may be improved resulting to more regular and for longer periods switch-off states. This effect can of course be generalised to include the backhaul network entities as well.

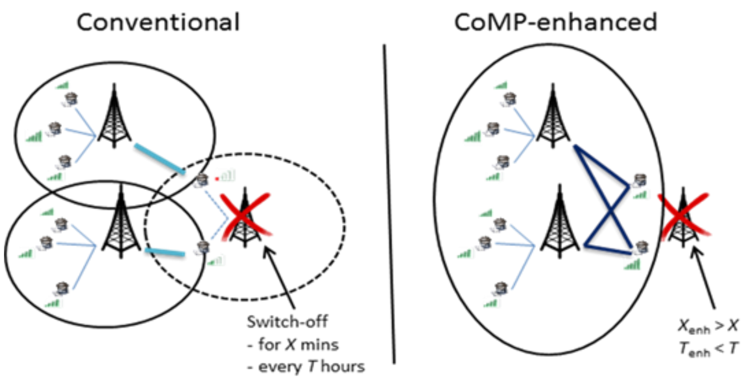


Figure 5-8: CoMP-enhanced vs. Conventional switch on/off scheme.

CoMP-enhanced System Model and Architecture

The downlink of a CoMP-enabled cellular system with M_S iSCs is considered. Also, M_m macro eNBs are overlaid in order to provide coverage to UEs that cannot be served by iSCs. To facilitate adaptive CoMP clustering, RANaaS platform operates as a central clustering unit in the system with main task to determine and adapt CoMP-clusters1 according to the specific system optimisation objectives and constraints. We also consider that RANaaS platform has access to data intended for UEs in the cluster and CSI among cluster iSCs and UEs, therefore, clustering, scheduling and precoding decisions can be performed there. Figure 5-9 illustrates the considered system architecture.

There are several schemes for CoMP transmission, each with varying degree of information exchange needs and way of distribution of this information. In this work, we consider the JT scheme in downlink where precoded data symbols from multiple iSCs, forming a CoMP-cluster, can be jointly transmitted to CoMP-enabled UEs such that desired data signals overlap to harness intra-cluster interference. Therefore, we focus on the case of coherent symbol combining, achieved through the application of precoding filters at iSCs to align the phases of signals transmitted from the multiple coordinating antennas.

To devise the joint precoded transmission, full Channel State Information (CSI) knowledge at the cooperating iSCs is required prior to the transmission, i.e. the compound cluster channel matrix between the iSCs and UEs involved in the JT procedure of each cluster. A CSI estimation process is required in that case. In time division duplex (TDD) mode, the channels can be considered reciprocal in uplink and downlink.

[1] A CoMP-cluster is defined as a set of cooperating iSCs, i.e. iSCs forming a CoMP-cluster exchange information and coordinate their transmissions (through the RANaaS Platform) in order to harness the offered diversity from multiple signal paths.

Therefore, CSI can be directly extracted from UE transmissions in uplink. In the non-reciprocal frequency division duplex (FDD) mode, the respective iSCs need to provide CSI reference signals (RSs) to CoMP-served UEs. Then, the UEs can estimate the downlink channel and provide CSI feedback to their serving iSC in uplink.

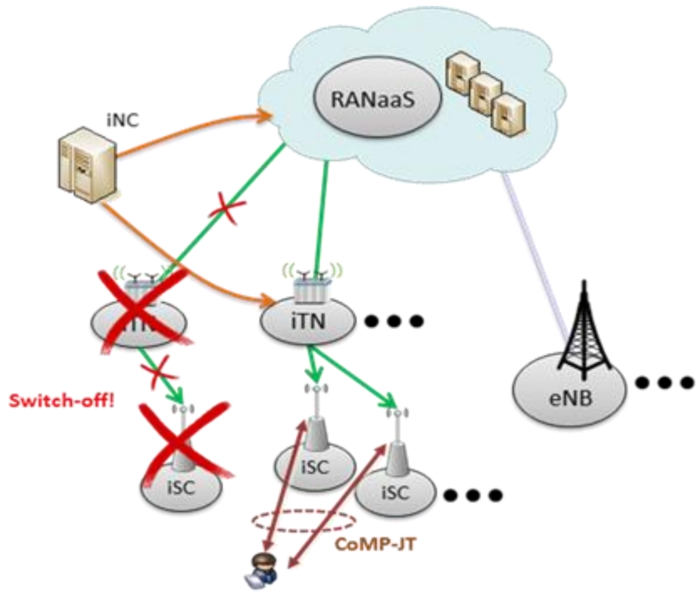


Figure 5-9: System Architecture

In this work, we examine the cases where CoMP-clusters are adapted dynamically in order to adequately serve UEs of underutilised iSCs that should be switched-off. After clusters are formed, all serving-iSCs of a UE need to acquire the same data and signalling information. In the RANaaS architecture, this can be done in a centralised manner to keep the network traffic same to that of a conventional system and to avoid increased processing complexity at cooperating iSCs. In such centralised approach, RANaaS platform has to receive UE data from the core network. At a next step, following the aforementioned centralised information acquisition process, RANaaS needs to distribute all CoMP-relevant data, i.e. JT-served UE data along with appropriate scheduling information (i.e., allocated PRBs), selected modulation and coding scheme (MCS) and precoding information, to the iSCs. Thus, the cooperating iSCs only need to receive a copy of the pre-processed data via the RANaaS platform and the backhaul network. In the end, the coordinating iSCs jointly transmit precoded data symbols to denoted CoMP-served UEs such that the desired signals overlap coherently and intra-cluster interference at these UEs is partially cancelled out.

System Power Consumption Model

In order to investigate the potential gains (from an energy performance perspective) of the proposed CoMP-enhanced scheme compared to the conventional one, we introduce a generalized system power model considering the sum of all power consumption contributions in the network following the iJOIN architecture. This will help us to evaluate the system power consumption (and later the potential benefits in terms of energy efficiency) when network elements switch off and iSCs load[2] conditions change based on the scheme adopted.

Considering the RANaaS system architecture, comprising M_S iSCs in total, its overall power consumption can be modelled by:

[2] Cell load under this work can be considered interrelated to the total generated data rate among all (dedicated or best-effort) flows from all served users in the cell over the peak data rate the iSC can accommodate.

$$P_{\text{Total}} = P_{\text{RANaaS}} + P_{\text{Bh}} + \sum_{n=1}^{M_S} P_{\text{iSC}-n} \quad (1)$$

Where P_{RANaaS}, P_{Bh}, and P_{iSC-n} stand for the power consumed at the RANaaS platform, the power needs for backhauling network, and the power usage at any iSC n, respectively. In the following, the power consumption of each individual network element is discussed.

iSC Power Consumption

The FP7 EARTH has investigated how the power consumption of distinct components of several eNBs, such as power amplifier (PA), baseband engine (BB), Radio Frequency (RF) small-signal transceiver, direct-current (DC)-DC converter, main supply (MS), and active cooling (CO), depends on the transmission bandwidth, the transmission power, and the number of radio chains/antennas [15]. According to this study, the maximum power consumption of a single eNB sector can be given by [16]:

$$P_{\text{eNB}} = \frac{P_{\text{BB}} + P_{\text{RF}} + P_{\text{PA}}}{(1-\sigma_{\text{DC}})(1-\sigma_{\text{MS}})(1-\sigma_{\text{CO}})} \quad (2)$$

where P_{BB}, P_{RF}, P_{PA} and σ_{DC}, σ_{MS}, σ_{CO} denote the power consumption and loss factors, respectively, of the different components. Furthermore, it was found that an affine function of the transmission power (comprising a static and a linearly increasing load-dependent share) can approximate very well the generalised model of eNBs [17], i.e.,:

$$\mathrm{P}_{eNB} = \begin{cases} P_0 + y \cdot \Delta_p \cdot P_{\max} & \text{if } 0 < y < 1 \\ P_{\text{sleep}} & \text{if } y = 0 \end{cases} \quad (3)$$

where P_0, P_{max} and P_{sleep} stand for the eNB power consumption at zero load, full load and sleep mode (considering that eNBs may enter a low consumption sleep mode where some of their main units are turned off when no data is received or transmitted), respectively. Furthermore, y and Δ_p denote the cell load and the slope of the load-dependent linear model.

To approximate iSC power consumption, we have adopted and combined the aforementioned models and we have taken into account that: *i)* the BB and RF power consumptions scale linearly with the system bandwidth (W) and the number of antennas (N_{ant}) used [18], *ii)* PA power consumption can be approximated as a linear function of the PA output power, and *iii)* no active cooling is needed in that case. Moreover, for simplicity, we have considered that only the PA is turned off when an iSC goes to sleep mode (i.e. no BB engine reductions due to sleep mode are considered). Therefore, the power consumption of an iSC n with cell load y_n can be given by:

$$P_{\text{iSC}-n} = \begin{cases} \dfrac{N_{\text{ant}} \dfrac{W[\text{MHz}]}{10}\left(P'_{\text{BB}} + P'_{\text{RF}}\right) + y_n P_{\text{PA}-\max}}{(1-\sigma_{\text{DC}})(1-\sigma_{\text{MC}})} & \text{if } 0 < y_n < 1 \\ P_{\text{sleep}} & \text{if } y_n = 0 \\ 0 & \text{if iSC switchoff} \end{cases} \quad (4)$$

where P'_{BB} and P'_{RF} denote the BB and RF base consumptions (i.e. using 10MHz and one antenna) while P_{PA-max} is the PA maximum transmission power.

In general, we consider that an iSC may implement only a portion of the eNB protocol stack. Therefore, its power consumption will be lower and upper bounded by the two extreme cases: a) Radio Remote Head (RRH) and b) baseline Small Cell, respectively. RRHs are considered as low complexity and processing nodes that solely perform RF operations and rely on self-backhauling (i.e. $P_{BB} = 0$ in that case). On the other hand, baseline small cells perform all the BB operations.

RANaaS Platform Power Consumption

In order to obtain an accurate estimation on the power consumption of the RANaaS platform due to BB processing[3] moved from iSCs, we make use of the commodity hardware consumption coming from the IT world; Fit4Green has investigated the power consumption for IT resources of data centres [19]. In particular, results for the various computing style servers are provided using a monitoring tool and a generic power consumption prediction model. Considering the measurements results for the cloud computing test-bed hardware equipment as the closest paradigm for the BBUs at a RANaaS platform, it can be observed that a linear model can approximate well a server's power consumption (P_{srv}) versus its percentage CPU usage (x_{srv}%).

$$P_{\mathrm{srv}} = P_0^{\mathrm{srv}} + \Delta_p^{\mathrm{srv}} P_{\mathrm{max}}^{\mathrm{srv}} x_{\mathrm{srv}} \tag{5}$$

where P_0^{srv} and P_{max}^{srv} denote the power consumption of the server when in idle mode and maximum usage, respectively, while Δ_p^{srv} stands for the slope of the equivalent linear power model which depends on the specific server considered.

Considering the RANaaS BBU as an enclosure hosting several identical interconnected ISS Blade servers (each considered as a set of multiple processors) equally sharing the requested workload, the servers' processing capacity (X_{Cap}), in Giga-Operations-per-Second[4] (GOPS), will define the total number of servers (N_{srv}) required to process the system BB-related workload (X in GOPS) moved to RANaaS BBU, i.e.:

$$N_{\mathrm{srv}} = \left\lceil \frac{X}{X_{\mathrm{Cap}}} \right\rceil \tag{6}$$

and the percentage CPU usage at each server will be:

$$x_{\mathrm{srv}} = \frac{X}{X_{\mathrm{Cap}} N_{\mathrm{srv}}} \cdot 100\% \tag{7}$$

The question that arises next is how the extra RANaaS BBU workload can be related to cell load. In that regard, the work in [18] considered the functionalities of various base station types and examined how the GOPS per function block scale with cell load for a specific reference system. Targeting to a more generalized view, Werthman et al. defined recently the resource effort required to serve a UE at a specific time as a function of the number of used antennas, the modulation bits, the code rate, the number of spatial MIMO-layers and the number of allocated frequency/time resources each as allocated to the UE at that time [20]. Based on this work, we introduce an average sum to approximate the total extra RANaaS BBU workload required to serve all UEs when an average β_{BB}% of BB processing is assumed to be moved towards RANaaS platform from each iSC. To this end, the GOPS required at RANaaS platform will depend on the total number of iSCs in the system, the load of each iSC, the system bandwidth, the number of antennas used to serve a UE per iSC (N_{Tx}), the average number of data bits per symbol per user (e_{MSC}) and the average number of MIMO layers per user (e_{MIMO}):

$$X = \sum_{n=1}^{M_s} X_n(y_n) = \frac{\beta_{\mathrm{BB}}}{100} \cdot \frac{W}{10[\mathrm{MHz}]} \left(30 N_{\mathrm{Tx}} + 10 N_{\mathrm{Tx}}^2 + 20 \frac{e_{\mathrm{MSC}}}{6} e_{\mathrm{MIMO}} \right) \sum_{n=1}^{M_s} y_n \tag{8}$$

Therefore, for any RANaaS BBU comprising servers with specific processing capacity, its overall power consumption due to BB processing moved towards RANaaS platform will be the sum of the power consumption at each of the required servers:

[3] Note that for fair comparison, we consider as power consumption of the RANaaS platform only the extra power needed for computations due to BB processing moved to RANaaS from iSCs (e.g at a RANaaS BBU). Other functionalities at RANaaS platform can be assumed that exist also at the core network of a conventional system.

[4] It is noted that the processing capacity of the server is usually expressed in GFLOPS [45]; however, it can be converted in GOPS, and in this work we use a 1:1 ratio as a conservative estimation.

$$P_{\text{RANaaS}} = \left\lceil \frac{X(y)}{X_{\text{Cap}}} \right\rceil \left(P_0^{\text{srv}} + \sum_{n=1}^{M_s} y_n \frac{\frac{\beta_{\text{BB}} W}{10^3}\left(30 N_{\text{Tx}} + 10 N_{\text{Tx}}^2 + 20 \frac{e_{\text{MSC}}}{6} e_{\text{MIMO}}\right)}{X_{\text{Cap}} \left\lceil \frac{X(y)}{X_{\text{Cap}}} \right\rceil} \Delta_p^{\text{srv}} P_{\max}^{\text{srv}} \right) \tag{9}$$

Backhaul Power Consumption

The last important element that we have modelled is the backhaul network. In general, centralised systems have notable backhaul load; therefore, power consumption due to data transport and switching can become a significant percentage of the total system power consumption [21].

Monti et al. provided some fundamental power consumption models for data transport through various backhaul technologies and topologies in small cells [22]. Considering self-backhauling iSCs with microwave links and omitting TNs for simplicity, the backhaul power consumption can be estimated by adjusting the respective model in [22] to our system architecture paradigm. In our case, backhaul power consumption shall scale with the number of iSCs in the system, the load of each iSC, the number of microwave antennas at each iSC n (N_{mw}^n), the power for transmitting and receiving the aggregate backhaul traffic at each iSC (P_{link}^n) and the power consumption of switches at each iSC (P_{switch}^n) aggregating traffic from other iSCs in case more than one backhaul link originates at the reference iSC, as:

$$P_{\text{Bh}} = \sum_{n=1}^{M_s} P_{\text{switch}}^n(y_n) + N_{\text{mw}}^n P_{\text{link}}^n(y_n) \tag{10}$$

Note that the power consumption at any switch will depend on the aggregated traffic at the associated iSC and its maximum capacity (Y_{max} in Gbps):

$$P_{\text{switch}}^n = \begin{cases} 0, & N_{\text{mw}}^n = 1 \text{ or } y_n = 0 \\ P_s \left\lceil \frac{y_n Y_{\max} f_{\text{cell-Bh}}}{C_{\text{switch}}} \right\rceil, & \text{otherwise} \end{cases} \tag{11}$$

where P_S stands for the switch basic power consumption and $f_{\text{cell-Bh}}$ is a factor denoting the relationship between backhaul traffic load and cell load.

Moreover, the power consumption for transmitting and receiving the aggregate backhaul traffic will generally depend on the traffic conditions. In this work, we consider that backhaul links can have an idle mode (i.e. when no data needs to be transported through backhaul) and a two-step function (low/high capacity traffic), where the two capacity regions are distinguished by a single threshold (C_{thr}):

$$P_{\text{link}}^n = \begin{cases} P_{\text{idle}}, & y_n = 0 \\ P_{\text{low-traffic}}, & 0 < y_n \le \frac{C_{\text{thr}}}{Y_{\max} f_{\text{cell-Bh}}} \\ P_{\text{high-traffic}}, & y_n \ge \frac{C_{\text{thr}}}{Y_{\max} f_{\text{cell-Bh}}} \end{cases} \tag{12}$$

CoMP Energy Consumption

The CoMP-JT scheme, where the UE data need to be available at all CoMP-cluster iSCs, is the most demanding CoMP scheme in terms of processing needs and backhaul bandwidth, and equivalently energy consumption, since this vast amount of information has to be centrally processed and transferred via the backhaul network. For a more accurate evaluation of the proposed solution, these factors have to be taken into account.

We can evaluate the effect on energy consumption when CoMP strategy c is employed as:

$$P_{\text{CoMP}-c} = \sum_{n \in \mathfrak{M}} \left(P_{\text{iSC}-n}(y_{i,c}) - P_{\text{iSC}-n}(y_i) \right) + (P_{\text{RANaaS}-c} - P_{\text{RANaaS}}) + \\ + (P_{\text{Bh}-c} - P_{\text{Bh}}) \tag{13}$$

The first term in the right hand side of equation above regards the power consumed at iSCs. This power depends on the iSCs changed load or state (i.e. considering active, sleep and switch off states) when CoMP strategy c is employed.

Furthermore, the second term in equation has to do with the extra signal processing needed at RANaaS in order to facilitate the chosen CoMP clusters. Assuming that $a_1 = 10\%$ of the overall processing complexity is due to the uplink channel estimation (scaling linearly with M_q) and $a_{12} = 1 - 10\%$ comes due to UL/DL MIMO processing (scaling linearly with M_q^2 per iSC) [23], we can estimate the extra processing required for each cluster i as:

$$X_{q,c} = \left((1 - a_1 - a_2) + a_1 M_q + a_2 M_q^2\right) \sum_{i \in \mathfrak{M}_{q,c}} X_i(y_{i,c}) \quad (10)$$

The processing needed for the remaining cells is considered 1) unchanged for cells not participating in a CoMP-cluster and 2) zero if the cell switches-off. Thus, assuming that all BB resources are pooled at RANaaS, we can map the processing effort needed for CoMP enabled strategy c into RANaaS energy consumption.

Finally, the third term regards the change in backhaul energy consumption. Under CoMP strategy c, iSCs in a cluster have a changed cell load which translates into new backhaul link traffic. Furthermore, iSCs that switch-off are also assumed to have associated backhaul links at idle mode during that period.

5.3 CT4.3: Joint Path Management and Topology Control

In CT 4.3, Joint Path Management and Topology Control, the fundamental problems to solve are to position (location), to dimension (CPUs) RANaaS data centres, and to associate each RANaaS with a particular set of iJOIN Small Cells (iSC). The optimal position and size of each RANaaS data centre will impact backhaul load, cost-efficiency, and resiliency within the network. Furthermore, most functionality provided by the iNC will be affected, e.g. path computation and mobility. This section provides a detailed overview on different options to deploy RANaaS data centres, side-constraints of their placement, as well as benefits and drawbacks. In addition, as path computation is essential part of this placement study, we provide a detailed overview of existing path-computation technologies which are applicable to iJOIN. Finally, a detailed description of the underlying algorithm for determining the optimal placement is provided.

5.3.1 Scenario

The network architecture is shown in Figure 5-10. There are two scenarios considered. As shown in the upper part of Figure 5-10, the backhaul connectivity of iSCs is deployed by extending the existing transport infrastructure which connects the macro cell base stations (eNBs) to the core network. Typically, fibre and microwave radio are deployed in the infrastructure. Such scenario, combining small and macro-cell layers, is referred to as an “Extended Legacy Network.” The deployment of small cell base stations in addition to the existing macro cell layer is for offering a better coverage or higher capacities in hotspot areas.

Alternatively, iSCs may be connected directly to the existing or newly deployed backhaul infrastructure, as shown in the lower part of Figure 5-10. This scenario is referred to as “Small Cell Greenfield Deployment.” The difference between scenarios is that in small cell greenfield deployment, the fixed networks are used for the hand-off from the dedicated backhaul network of small cells to the existing infrastructure [24]. The reason for studying them is that the design choices may vary a lot when different scenarios are applied.

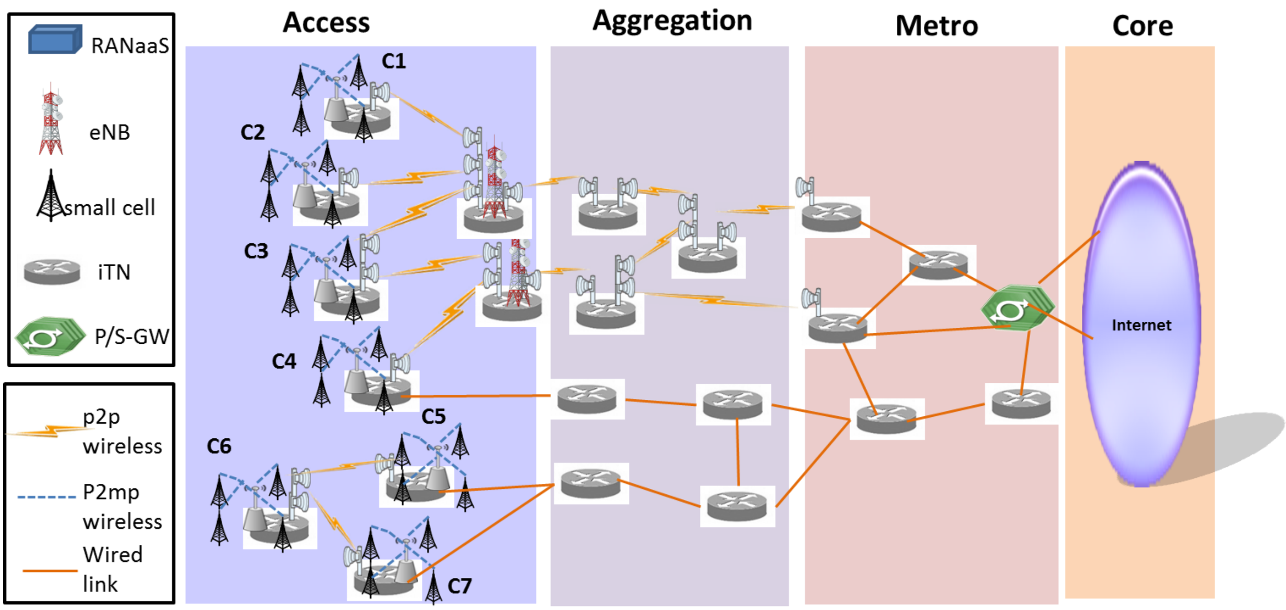


Figure 5-10 Considered network architecture for RANaaS placement study

A small cell Cluster is defined as a hub transceiver forming point-to-multipoint wireless links to a number of small cells. The hub capacity is shared across the small cells. As shown in Figure 5-10, there are seven small cell clusters, {C1, C7}. Clusters C1, C2, C3 and C4 are in the extended legacy network and clusters C5, C6 and C7 are in the small cell Greenfield deployment.

By optimally positioning/dimensioning RANaaS platform results in more efficient path management (Utilisation Efficiency) and more economic RANaaS deployment (Cost Efficiency). The impact on latency, computation resources as well as path computation are further analysed to demonstrate how optimal RANaaS deployment can achieve iJOIN objectives on Utilisation Efficiency and Cost Efficiency.

To minimise anchors, RANaaS platform should be co-located with another data plane function. In our study, three candidate locations are investigated:

- Case 1: RANaaS platform co-located with eNB (Figure 5-11)
- Case 2: RANaaS platform co-located with aggregate iTN (Figure 5-12)
- Case 3: RANaaS platform co-located with P/S-GW (Figure 5-13)

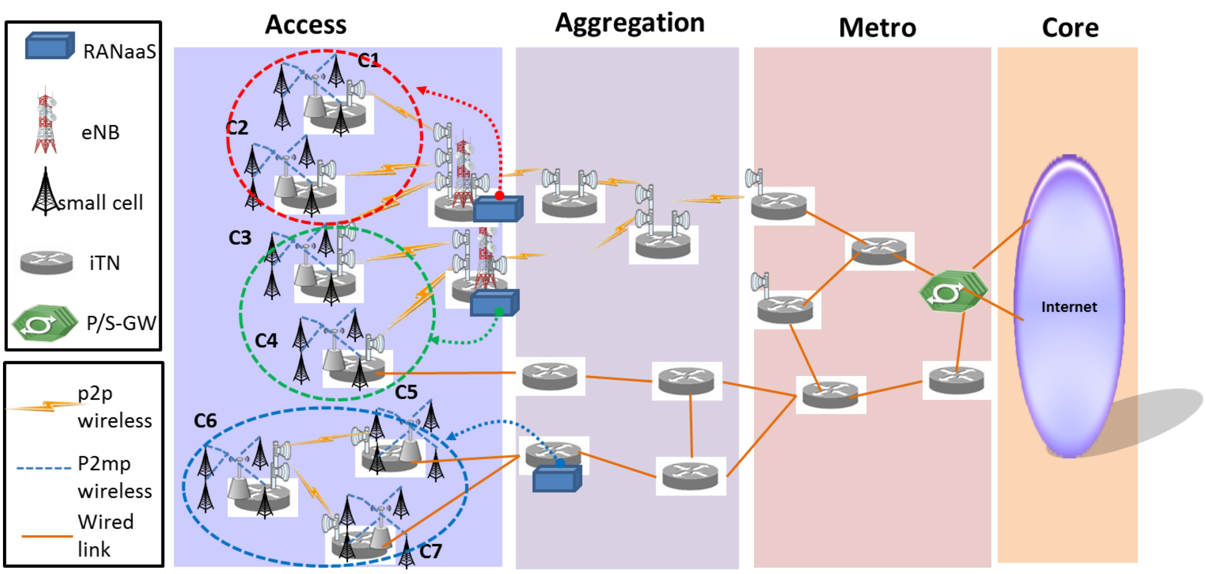


Figure 5-11 Case 1: RANaaS platform co-located with eNB

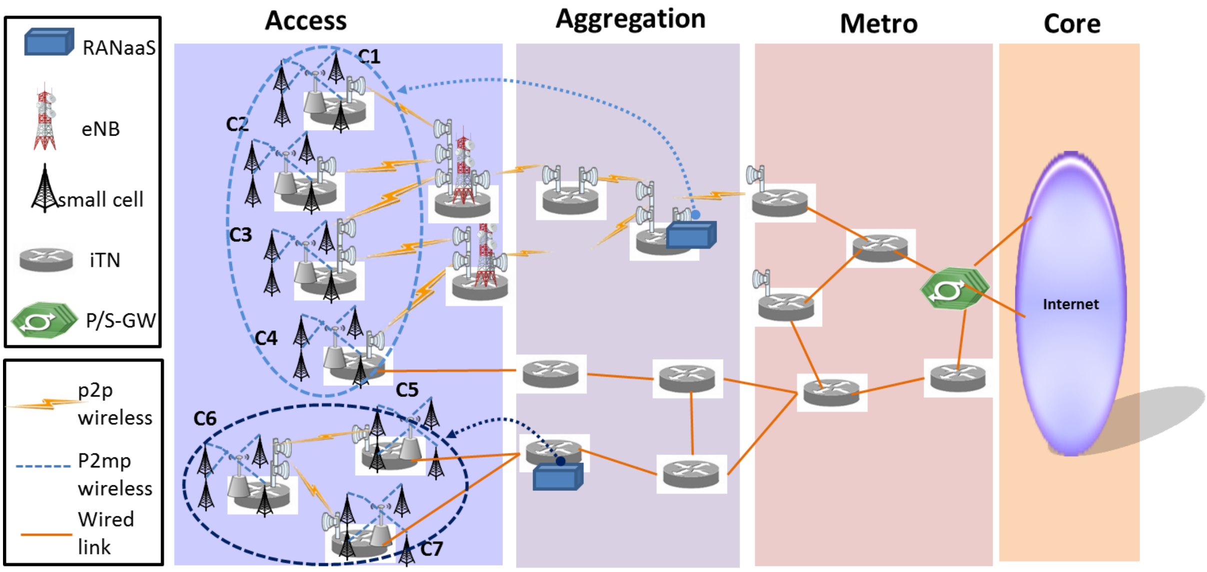


Figure 5-12 Case2: RANaaS platform co-located with iTN

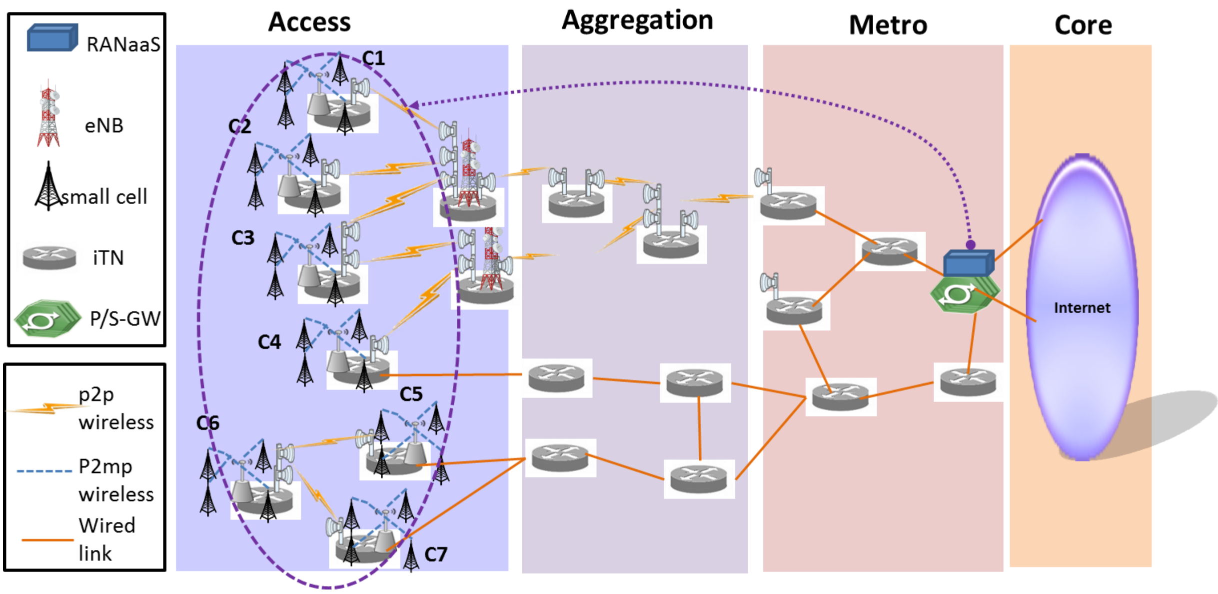


Figure 5-13 Case3: RANaaS platform co-located with P/S-GW

Latency

In the latency analysis, we assume that the latency increases with the number of hops between two nodes. As shown in Figure 5-14, the latency between the RANaaS platform in P/S-GW and the iSC is the largest, while the latency is the smallest when placing the RANaaS platform in the nearby eNB.

Computation Resources

We assume that the computation resources increase with the amount of traffic processed by the RANaaS platform. In other words, the more traffic is processed by the RANaaS platform, the more computation resources are required in the RANaaS platform.

In order to fulfil the requirements of the users regardless of time and space, network operators usually deploy the networks to support peak traffic demands. Nevertheless, peak traffic for aggregating N small cells is not equal to N times peak traffic of one small cell because not all small cells will be simultaneously busy (in peak traffic demand). As shown in Figure 5-15, the peak traffic of small cell clusters {C1, C2} and {C3, C4} is 100Gbps. However, the aggregated traffic of small cell clusters {C1, C2, C3, C4} is 150Gbps, instead of 200Gbps. Therefore, when more small cells are associated to one RANaaS, more “statistical multiplexing gains” can be utilised. Consequently, less computation resources are required.

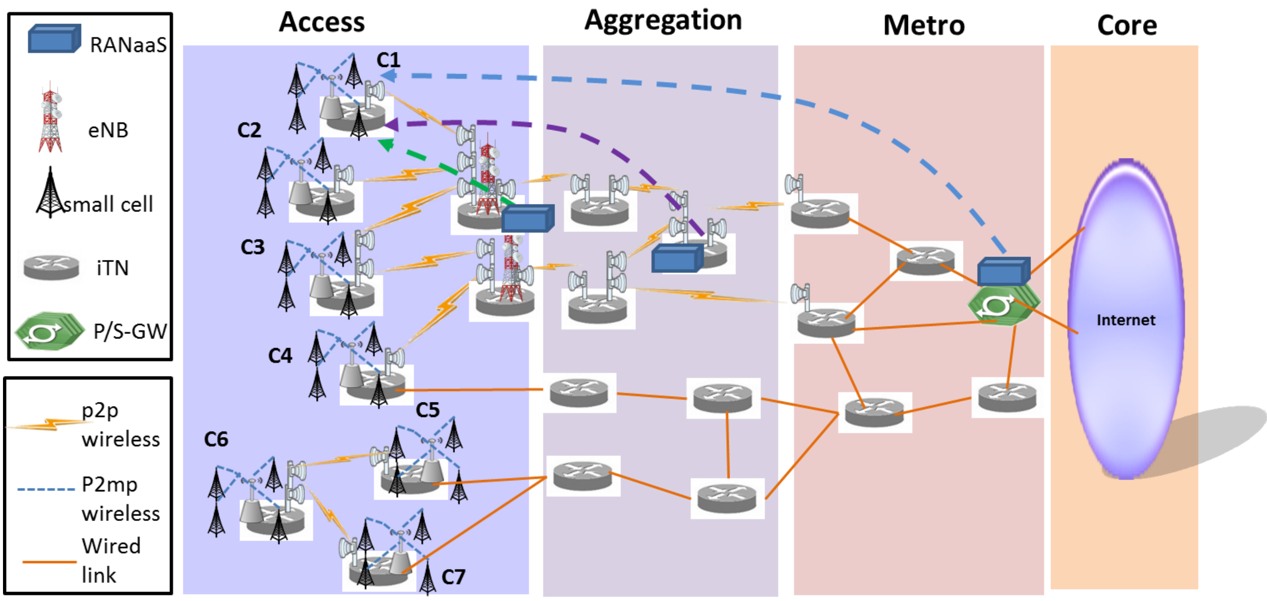


Figure 5-14 RANaaS impact on latency

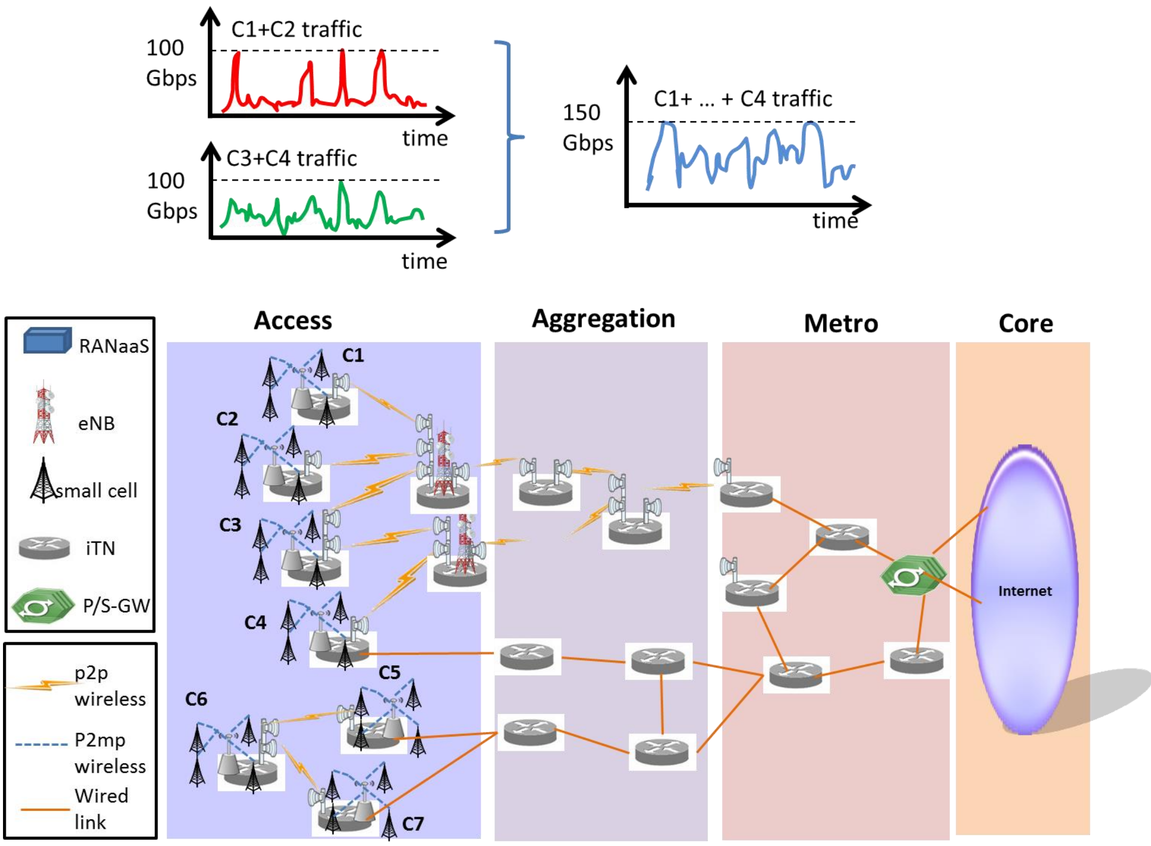


Figure 5-15 Statistical multiplexing gain of aggregated small cell clusters.

As shown in Figure 5-16, when RANaaS is co-located with the P/S-GW, the required amount of traffic processed by the RANaaS platform is 250Gbps. On the other hand, the required traffic processed by the RANaaS platforms is 350Gbps when a RANaaS platform is co-located with eNBs. Through this example, we can show that placing RANaaS in P/S-GW may require less computation resource than placing in iTN and eNB due to higher statistical multiplexing gains.

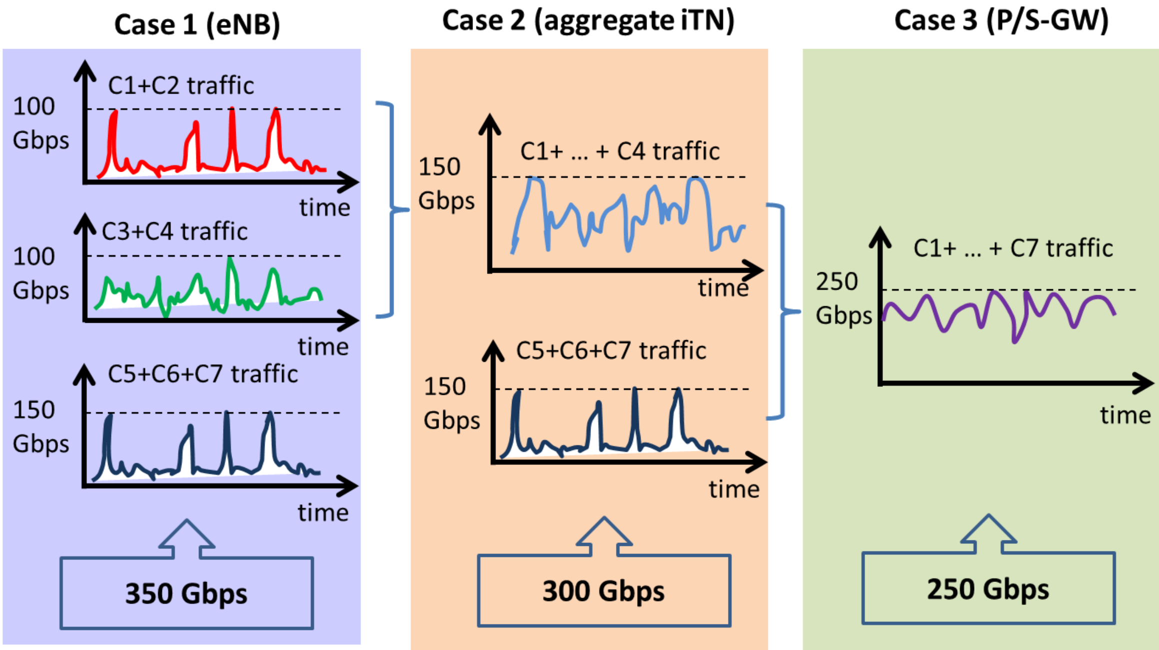


Figure 5-16 The effect of RANaaS placement on computation resources

Path Computation

Path-computation is considered from various angles of view. We first discuss the impact of data-offloading by comparing the three cases of no data offload, load breakout at iTN, and local breakout at eNB. Finally, we discuss relevant and applicable path-computation algorithms.

No data offload

In Figure 5-17, the purple line represents the shortest path from small cell cluster C3 to the core network. The red line represents the routing path from small cell cluster C3 to the core network when the RANaaS platform is located in iTN. When the RANaaS platform is co-located with the iTN, which is usually located in the middle of the backhaul network, this result in non-optimum routing compared to the shortest path. On the other hand, as the shortest path traverses through the eNB as well as P/S-GW, there is no side-effect of non-optimum routing when the RANaaS platform is located either close to the iSC (in eNB) or close to the access of the core network (in P/S-GW).

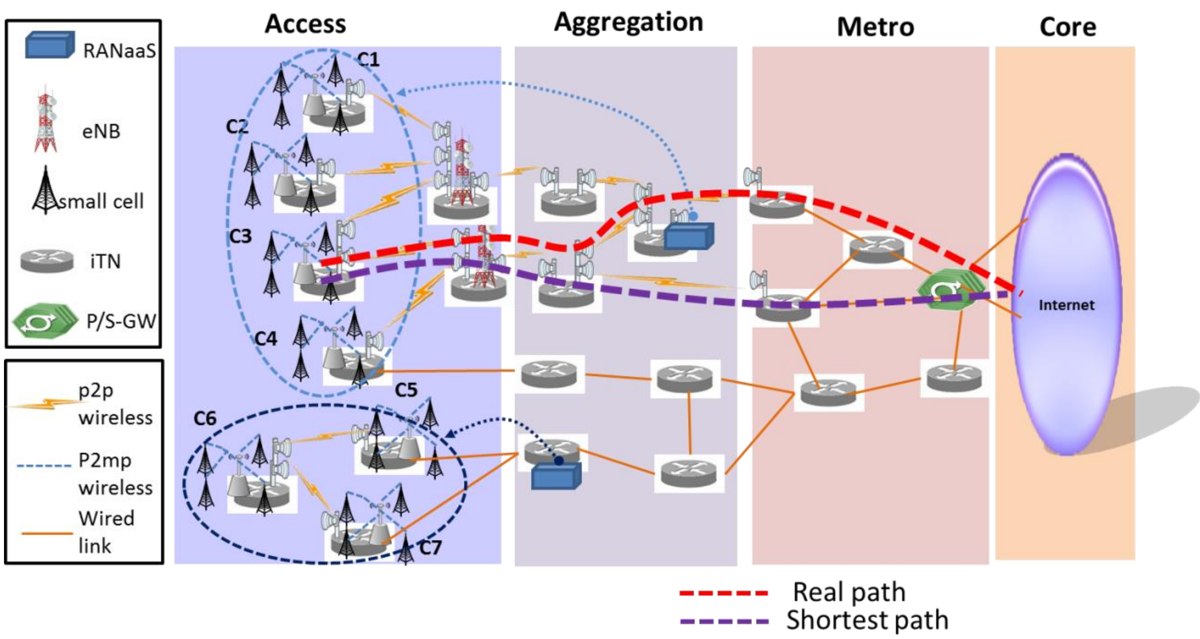


Figure 5-17 RANaaS impact on routing (without local breakout)

Local breakout at iTN

When considering the case of data offloading, the result of the routing becomes different. This is because the data traffic does not traverse through the backhaul network. Instead, it goes to the internet via a local gateway (iLGW). When the iLGW is placed in the iTN and RANaaS is placed before the iLGW (in iTN or in eNB), the routing path is short. However, as shown in Figure 5-18, when the iLGW is placed in iTN and RANaaS is placed in P/S-GW, not only the routing path is non-optimal, but also the iLGW loses its function for providing the prompt data offloading.

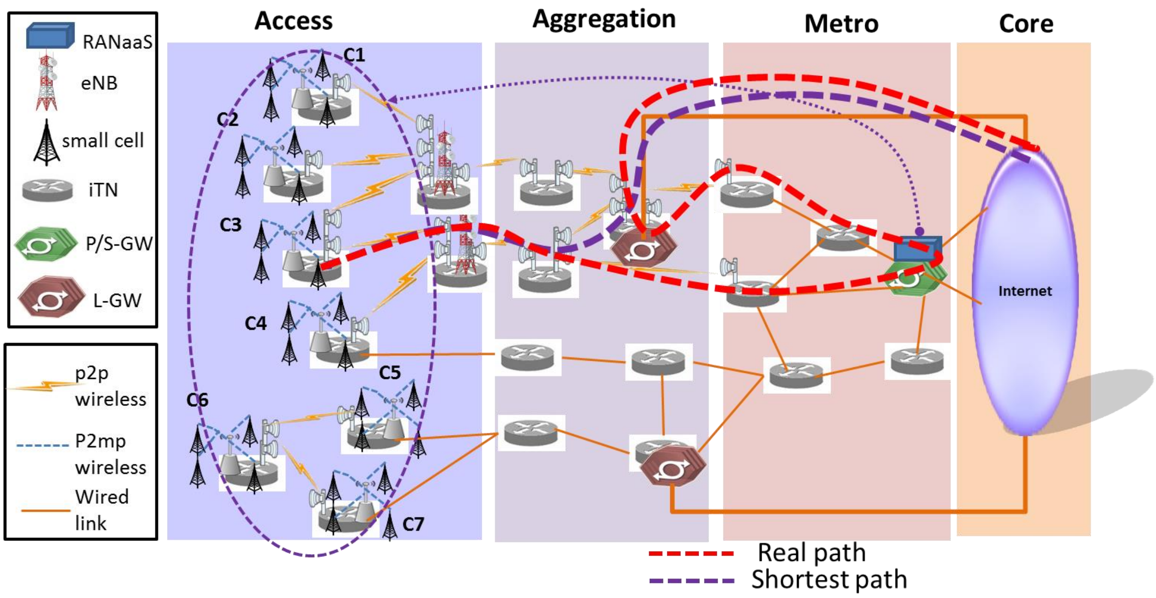
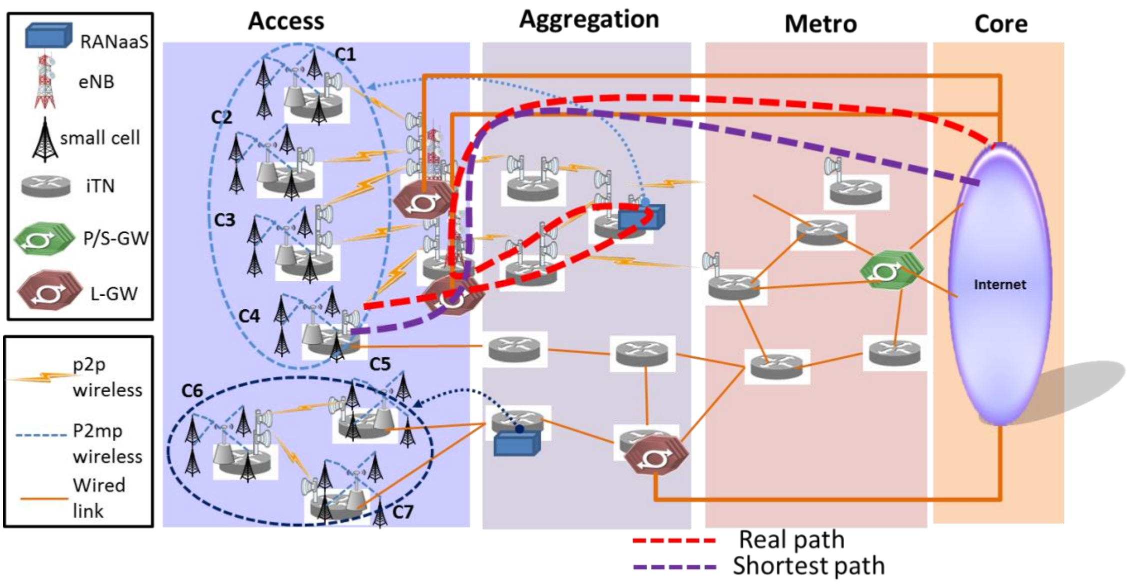


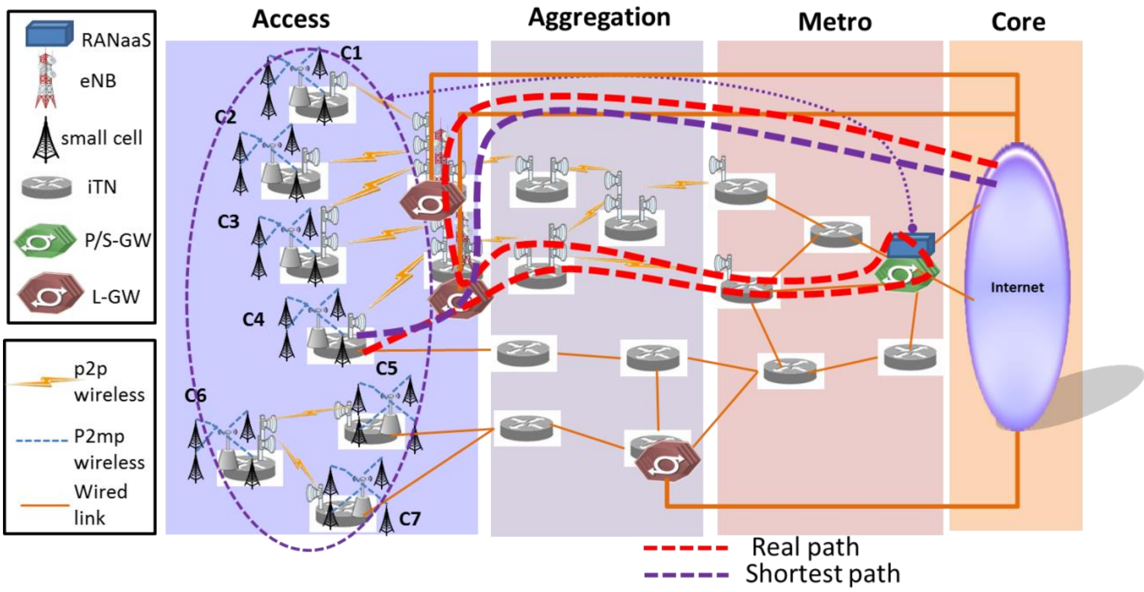
Figure 5-18 RANaaS impact on routing (with local breakout at iTN)

Local break-out at eNB

Similarly, when the iLGW is located in eNB and RANaaS is located in P/S-GW or iTN, the routing path detours, as shown in Figure 5-19. Only when the RANaaS is co-located with iLGW in eNB, the routing path is optimal and short.



(a) RANaaS platform co-located with iTN



(b) RANaaS co-located with P/S-GW

Figure 5-19 RANaaS impact on routing (with local breakout at eNB)

In conclusion, when local data offloading is provided in the network, the location of iLGW must be taken into account when planning the deployment of the RANaaS platforms. Especially, when the iLGW is located closed to the iSC, the RANaaS platform should be located not further than ILGW for avoiding the poor routing paths.

Relevant path-computation approaches

With the introduction of dense small cells deployments, backhaul networks become more and more a mobile network's bottleneck. Right now, operators struggle considerably to keep the capacity offered by their backhaul networks on a par with the rapidly increasing traffic demand of their mobile users. Traffic engineering (TE) is an important mechanism for operators seeking to utilise the network resource in an efficient way. Routing optimisation plays a key role in traffic engineering, searching for optimal routes in order to achieve the desired network performance. In this survey, traffic engineering algorithms in mobile backhaul networks are reviewed from the perspective of routing optimisation.

From the aspect of routing enforcement mechanisms, traffic engineering can be classified into MPLS-based TE and IP-based TE. OSPF, an IP-based TE, is the most widely used intra-domain routing protocol in today's Internet. OSPF assigns weights to links and computes the shortest path across the network (or the path with lowest weight). The basic idea is to set the link weights according to the given network topology and traffic demand so as to control intra-domain traffic and meet TE objectives. Unlike MPLS-based TE, which enables dedicated explicit routing for individual flows, such "fine-grained" path selection cannot be achieved in IP-based TE, as even small changes to link weights may have an avalanche effect causing significant impacts to the network [26].

Today, MPLS-based TE is a prominent technology in mobile backhaul networks. MPLS [27] is a flow-based packet forwarding technology, which assigns packet flows to Label Switched Paths (LSPs). The most distinct advantage of MPLS is its capability of explicit routing and arbitrary splitting of traffic. Using small labels which identify the route through the network, MPLS allows for fast routing and is able to handle heterogeneous networks (which requires a tight integration of MPLS and the underlying physical network). However, since traffic trunks are delivered through dedicated LSPs, scalability and robustness becomes an issue. More specifically, the overhead of setting up LSPs can be very high in large-size access networks, making it less scalable due to the large size of the routing tables (RIB). In [28], OSPF and MPLS are both combined. MPLS paths are used to distribute the traffic and OSPF is used locally which implies less frequent and less severe changes of link weights.

Constrained Shortest Path First (CSPF) [29] is an early MPLS-based TE approach without coordination between individual traffic trunks [30]. A CSPF algorithm operates as follows. Before setting up an LSP for a specific traffic trunk, all the infeasible network links (e.g., those with insufficient available bandwidth) are removed from the network topology. Shortest path routing (SPR) is then performed on the residual network graph, and the LSP is assigned to this shortest path. The algorithm repeats the above procedure until all the traffic trunks are assigned. Other routing schemes have also been proposed to extend SPR, such as Widest Shortest Path (WSP) and Shortest Widest Path (SWP) [31] [32], both of which try to increase the available bandwidth at bottlenecks along the path. By applying WSP/SWP, not only has the underlying traffic a higher probability of finding a feasible path, but also network bottlenecks are avoided by "reserving" bandwidth resources for future demands, benefiting other traffic from this more sophisticated routing strategy.

While CSPF may not result in optimal performance, some MPLS-based TE schemes have addressed the problem of minimising the maximum utilisation, which is often formulated as a linear or integer programming problem. Computing the optimal route in MPLS-based TE is computational complex and may not be done online. In [33] it has been proven that TE using multiple paths and arbitrary traffic splitting is able to achieve optimal solutions using linear programming, while integer programming can be applied to MPLS-based TE without LSP bifurcations. For ease the complexity of linear programming, [34] proposed to use genetic algorithm (GA) to compute paths.

Mechanisms for triggering search for feasible paths can be categorized into offline routing (pre-computation) and on-line routing (on-demand). In offline routing, routes to various destinations are maintained at all times, whether they are required or not. On one hand, offline routing is highly responsive because the overall average time of path setup is significantly reduced [35][36]. On other hand, it requires high processing and storage overhead. This is further complicated if frequent route re-computation is required. The problem of storage in offline multiple-path routing [37][38] is that routing tables grow dramatically. This necessitates using efficient mechanisms for storage and retrieval [39][40]. In online routing, routes to destinations are computed when they are needed. This approach reduces overhead, at the expense of slower response times. A combination of offline and online algorithms were presented in [41]. The authors in [41] introduced an algorithm which uses the expected traffic matrix to derive an optimal network topology offline, and an online component applies small, local changes based on dynamic traffic requests.

Current mobile backhaul adopts offline MPLS-based routing. In other words, the paths are pre-computed based on the peak traffic demand. This static approach works well for wireline backhaul networks with stable link capacities and networks with fairly stable traffic demands. However, in iJOIN, wireless links with changing link capacities (due to changes in the used modulation and coding scheme) are deployed and the traffic demand among small cells is fluctuating considerably. This leads to significant variations of the experienced traffic-capacity ratio and thus, if only offline TE was employed, to inefficient resource allocation. Therefore, the routing method in iJOIN is expected to select the optimal path both offline (based on predicted traffic demand information) and online (in case of burst traffic and link failure) while taking into account QoS as well as dynamic metrics such as traffic demand, available bandwidth, delay, reliability, jitter, and mobility aspects (such as proximity to nodes that can act as anchor/offloading points for certain types of flows).

SDN technology provides a framework to integrate different path computation algorithms vertically in the iJOIN architecture. In the iJOIN project, OpenFlow is adopted to realise the SDN-based backhaul network. Other than OpenFlow, it is also possible to achieve SDN with Path Computation Element (PCE) [42]. A PCE is a network entity which is capable of computing paths on behalf of the nodes in the networks. PCE might be a network node, network management station, or a virtualized entity running in a cloud. PCE applications compute label switched paths (LSP) for MPLS and GMPLS traffic engineering. The PCE architecture and PCE protocol are defined by the IETF in RFCs 4655 [42] and RFC 5440 [43], respectively.

5.3.2 Approach

System Model

In our RANaaS deployment study, we assume that all iSCs are centralized with RANaaS. Therefore, the traffic from iSC is processed firstly by RANaaS before going to the network. As we analysed previously, this may introduce the overhead to backhaul network since the traffic may not be routed through the optimal path from iSC to the gateway. We further assume that the upper bound of the latency between RANaaS and iSC is 10ms and the required backhaul bandwidth is at least 30Mbps. For computing the optimal RANaaS deployment, the traffic information and topology are given as inputs. The cost of the required data processing resource is defined as [13]:

$$(0.083 \times N \times \textit{usage rate} + 0.007) \times 40000$$

where N is the number of eNBs as well as iSCs, and the cost of each reference server unit is 40K USD.

Algorithm Design

To optimally locate and dimension the RANaaS in backhaul networks, a RANaaS deployment algorithm based on a genetic algorithm (GA) is proposed. The objective is to locate/dimension the RANaaS platforms in order to minimize the deployment cost.

A. Population Generation

In the GA, a population of genomes is maintained within search space. Each genome represents a candidate solution to a given problem. A solution in the GA population is initialized as follows:

- In order to reduce the complexity of the algorithm, 3-5 cells are randomly geographically grouped as a unit cluster as shown in Figure 5-20.
- Randomly group the adjacent unit clusters into multiple sets as shown in Figure 5-21.
- Randomly select a RANaaS location for each set as shown in Figure 5-22:
  1) Compute paths between each cell and RANaaS
  2) Check latency limitation of each path
  3) Check low-bound backhaul data rate can be fulfilled for each path
  4) If not, choose randomly another location until (2)-(3) are fulfilled

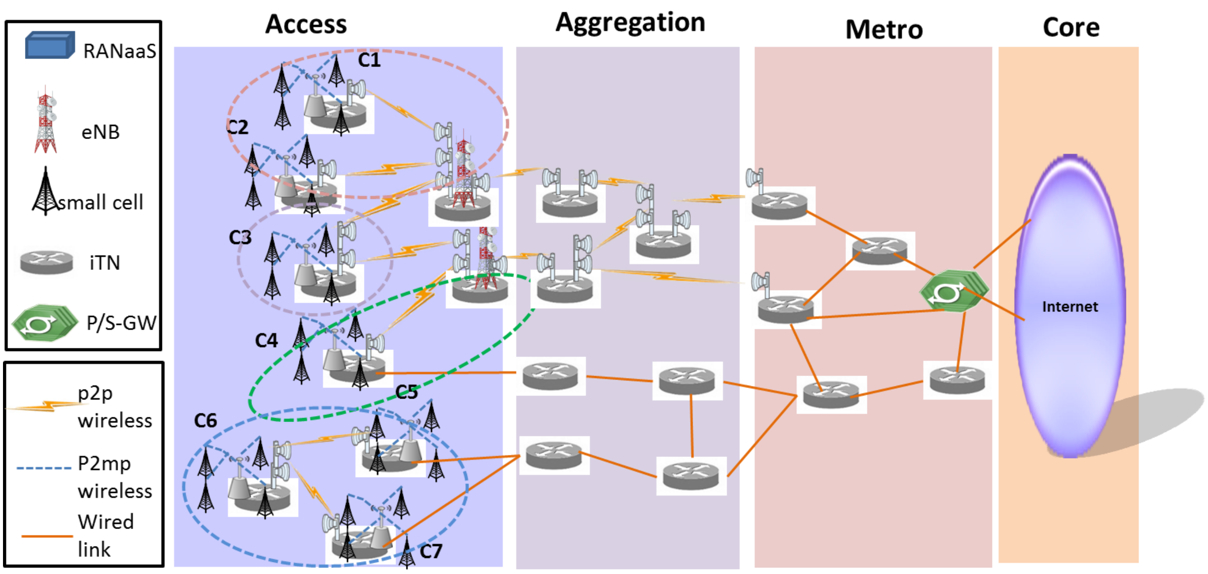


Figure 5-20 Population initialization Step 1: defining minimal cluster

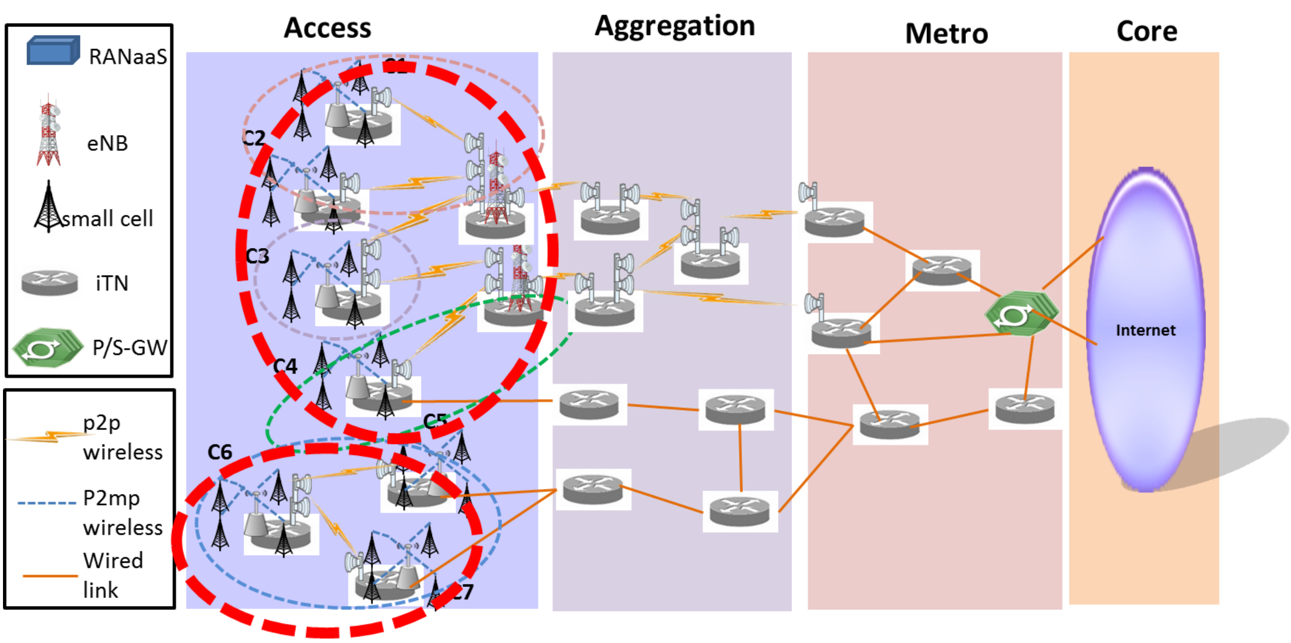


Figure 5-21 Population initialization Step 2: random grouping

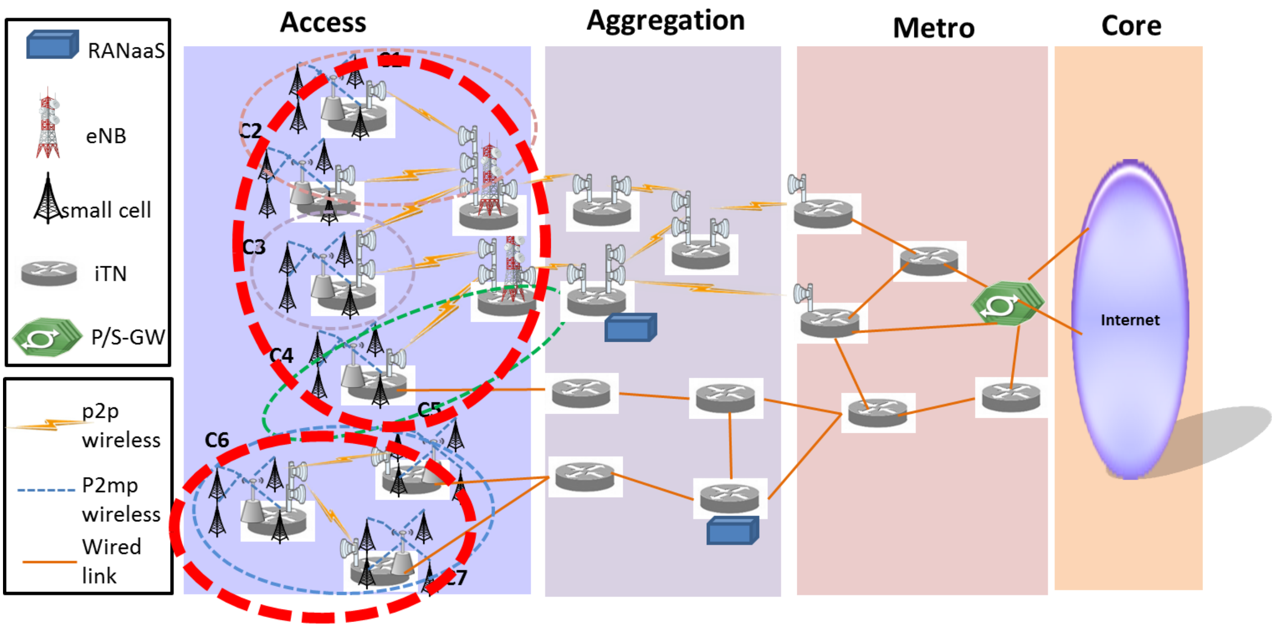


Figure 5-22 Population initialization step 3: random selection of location

B. Mutation

There are two ways of mutating a solution: changing the grouping or changing the RANaaS location. As depicted in Figure 5-23, mutation is achieved by randomly selecting two grouping sets and re-grouping them into two sets. Figure 5-24 shows that mutation is down by randomly selecting a RANaaS and changing its location. Note that each new result has to fulfil the limitation of latency and backhaul data rate. Otherwise, the process continues until a valid candidate solution is generated.

C. Crossover

Two candidate solutions S_1 and S_2 are randomly selected for performing crossover. The crossover operation is simply creating a new solution where the association of iSC clusters to RANaaS locations defined in solution S_1 or S_2.

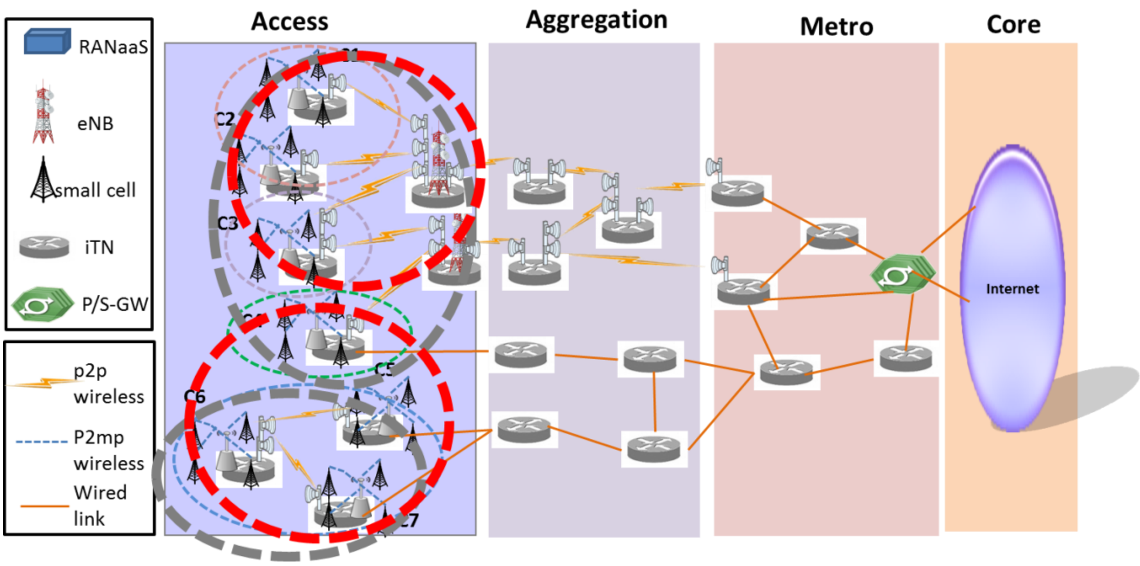


Figure 5-23 Mutation by changing grouping

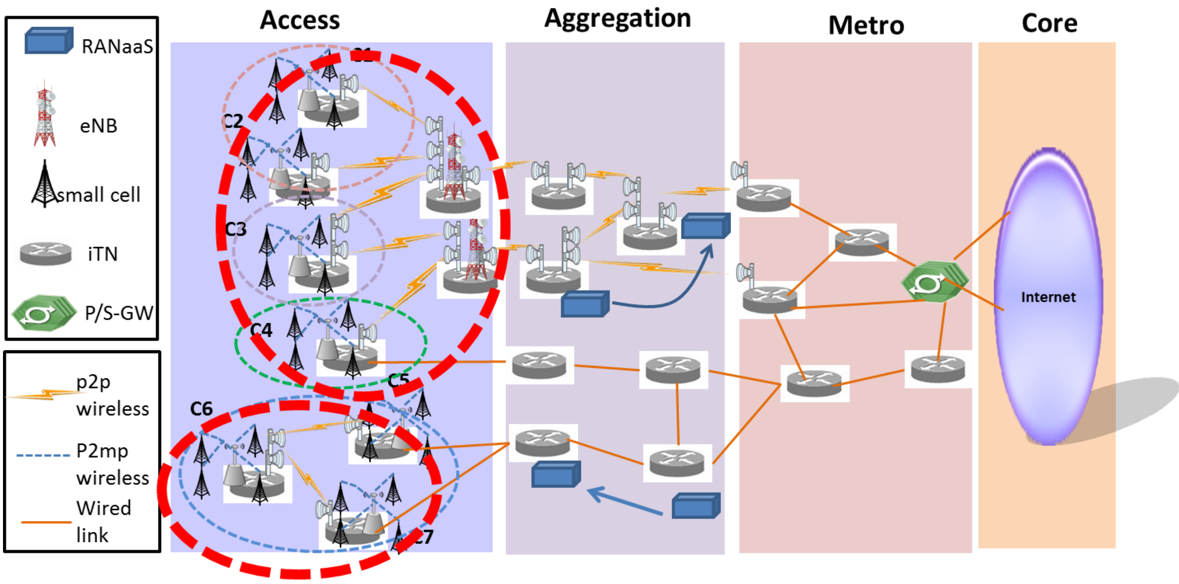


Figure 5-24 Mutation by changing RANaaS location

5.4 CT4.4: Routing and Congestion Control Mechanisms

The objective of this CT is to provide an adequate technical solution for the congestion control issues in the transport nodes that support RANaaS and flexible functional split. The development of this CT is motivated by the fact that actual congestion control mechanisms are not able to provide the required support for the iJOIN requirements.

Congestion control protocols have been developed in the context of IETF, focusing mainly on end-to-end mechanisms. IETF's TCP congestion control schemes in data networks were developed with a focus on a use of the Internet for reliable bulk transfer of non-time-critical data, such as transfer of large files. They have also been used successfully to govern the reliable transfer of smaller chunks of data in as short a time as possible, such as when fetching Web pages. These algorithms have also been used for transfer of media streams that are viewed in a non-interactive manner, such as "streaming" video, where having the data ready when the viewer wants is important, but the exact timing of the delivery is not.

For real time interactive traffic, the requirements are different; one needs to provide the data continuously, within a very limited time window (no more than 100s of milliseconds end-to-end delay, depending on the application), the sources of data may be able to adapt the amount of data that needs sending within fairly wide margins, and may tolerate some amount of packet loss, but since the data is generated in real time, sending "future" data is impossible, and since it's consumed in real time, data delivered late is commonly useless.

Research in this area has resulted in a number of promising congestion control variants. But, as it will be explained in the next subsection, the requirements of RANaaS information flows associated to different functional splits, coexisting over the same transport infrastructure, are different from those in current high speed packet networks. In this sense, they are closer to the requirements associated with data centres, which pose new demands on transport protocols and congestion mechanisms. However, there are some aspects that should be taken into account before adopting data centres' congestion control mechanisms for the iJOIN architecture:

- Unlike data centres, in the iJOIN network the latency is not necessarily dominated by queuing delays, but also by the time-of-flight.
- The traffic pattern in data centres is characterised by the coexistence of short messages that require very low latency and, large flows that require high throughput but are not delay sensitive. This is not a fair characterisation of RANaaS information flows.

5.4.1 Scenario

Congestion control mechanisms have been based on solutions embedded at the endpoints (mainly in TCP), aided occasionally by queue management and scheduling algorithms in bottleneck routers and switches that provide signals to the endpoints. For the reasons that will be explained in this section, these solutions are considered not to be adequate for coping with the new requirements associated to the iJOIN architecture.

For a congestion control mechanism in iJOIN network to be efficient, it should be able to handle in an effective way different kinds of flows associated with different functional splits, which may present different requirements in terms of capacity, maximum latency, etc. An example of this situation is represented in the following figure:

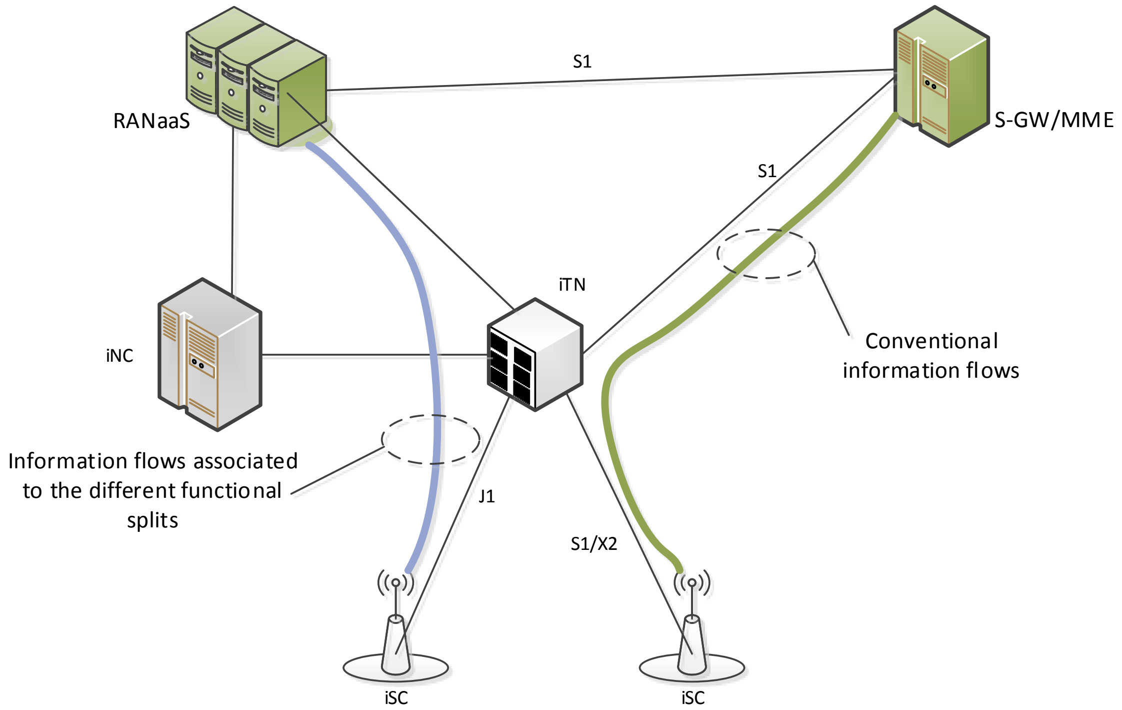


Figure 5-25 Congestion Control Example

It seems clear that coping with this kind of situations requires new technical solutions, closer to those employed in data centres than traditional congestion control solutions.

Two areas will be addressed in this section:

- Specific congestion control mechanisms for RANaaS flows associated with functional splits that present high performance requirement.
- Improvements of the congestion management mechanisms to be used for traditional flows (where no functional split is performed) or RANaaS flows which do not have critical requirements.

These two areas are logically interconnected, as the congestion management mechanisms of traditional flows may be employed, e.g., to signal potential congestion situations (if Explicit Congestion Notifications are used) detected with RANaaS specific mechanisms.

Main requirements

The congestion control mechanisms to be applied to RANaaS flows are intended to support the transport requirements associated to the different functional splits supported. They can be characterised by the following parameters:

- Capacity

Depending on the functional split, the capacity to be guaranteed may be fixed, if CPRI interface is used, or proportional to the number of users connected, if the functional split happens at or after the time-frequency conversion in the PHY layer.

Capacity requirements for representative functional split cases are:

- CPRI split: information is generated with the sampling frequency, which depends on the channel bandwidth and whether oversampling is applied. The amount of information that is generated in each sampling period is constant and it is determined by the number of bits per sample that are used in the

DAC/ADC. It can be assumed that a capacity of the order of >100 Mbit/s/MHz is required in this split. It can be reduced applying time based compression techniques or reducing the number of bits per sample in the analog/digital conversion.

- Split after FFT (UL) and before iFTT (DL): information is generated with the symbol frequency (seven symbols per 0.5ms slot with normal prefix and six symbols with extended prefix), and the volume depends on the number PRBs that are being used in a given sub-frame[5]. In full load conditions, and applying compression techniques, it can be expected a reduction of up to 50% in the capacity required from CPRI split.
- Intra-PHY split before decoding: information is composed by soft symbols and they are produced every TTI (1ms). The required bit rate is estimated to be of the order of 6x the information bit rate.
- PHY-MAC split: information blocks are generated every TTI (1ms) and the amount of information is basically equivalent to the traffic generated.
- RLC-PDCP split: information blocks are generated according to IP packet generation process. Information volume is very close to (but lower than, due to header compression when applied) the original IP flows.

It should be noticed that the flows associated to each functional split not only differ in the traffic volume generated but in the generation pattern – even it can be argued that they operate in different time scales.

- Latency: depending on the functional split, the latency to be supported can be larger or smaller. The fundamental factor to be considered is where the HARQ process is implemented, in the iSC or in the RANaaS entity. Latencies for flows where HARQ resides in the RANaaS entity should be compatible with the 3ms limit of the standard.
- Jitter: latency variation requirements will also be dependent on the functional split supported. However, it is not expected to be a significant issue (it may have some impact in functional splits where frame building is carried in the RANaaS entity).
- Synchronisation: when the RANaaS provides support for cooperative mechanisms, it is important that the flows arrive to their destination (the RANaaS entity or the cooperating iSCs) within a temporal framework that allows for supporting the implemented mechanisms. As it cannot be guaranteed that the latency between RANaaS entity and the cooperating iSCs is the same for all of the latter, some correcting mechanism should be employed. The main problem is associated with the support of Joint Transmission (JT) schemes.

The operating environment is represented (in a much simplified way) in the following figure:

[5] The number of PRBs is used is fixed in a given sub-frame, but the location can change in each of the slots of the sub-frame.

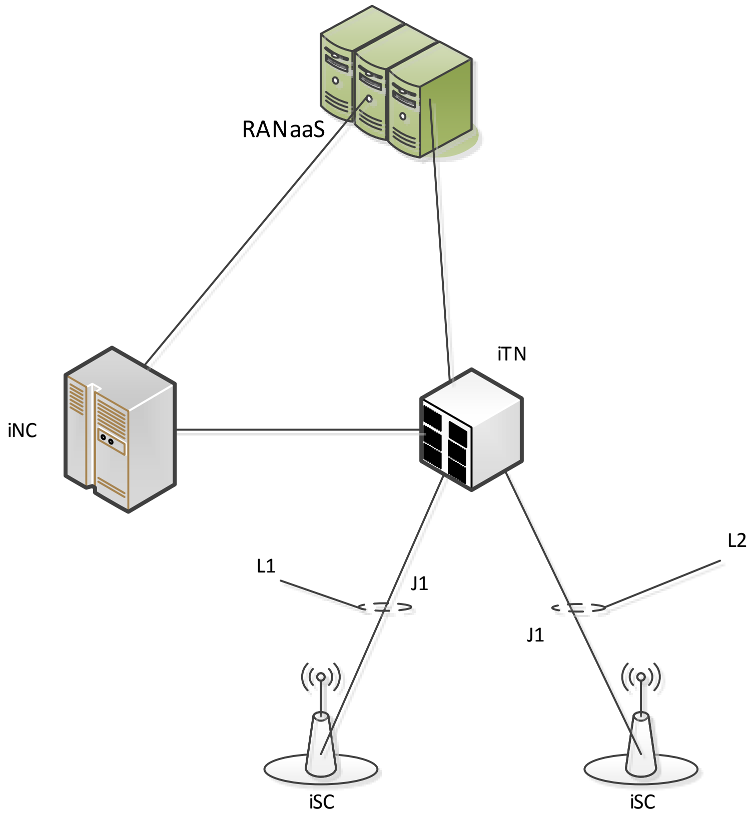


Figure 5-26 Operating Environment of Congestion Control

In the case of supporting JT, signals should be transmitted from each antenna simultaneously. Supposing that, e.g., L1 > L2, there mainly two ways to achieve this objective: the iSC are time synchronized so they are able to initiate the transmission on the same instant; or the iTN is aware of the latency difference of both links, and schedules the transmission to each iSC in a way that the information flows arrive simultaneously to both iSC (or within an acceptable bound).

The resulting set of requirements implies that new congestion control mechanisms should be used for an efficient operation of the system at a reasonable cost (i.e., without having to oversize the transport network to meet them).

5.4.2 Approach

The solution proposed is based on the virtual queue concept, which focuses on eliminating queues at all switch ports. The concept is motivated by the idea that it is possible to eliminate buffering and queueing delay by detecting congestion based on the link utilisation approaching its capacity, rather than the queue occupancy. The virtual (also called phantom in some implementations) queue represents an imaginary flow whose unused capacity can be used to accommodate traffic increases without queue build-up.

In terms of implementation, the virtual queue is a queue maintained at each switch egress port that sets ECN marks based on link utilisation. It simulates queue build-up for a virtual link running at a configurable speed slower than its physical capacity, without actually buffering any packets. The mechanism marks incoming packets with ECN when the simulated queue is above certain threshold, which is then utilized by the transport protocol to perform adaptive congestion control. Since the virtual queue deliberately caps the aggregated flow rate to be strictly less than the physical capacity, the switch buffers are kept largely unoccupied, and packets experience baseline transmission delay without queuing.

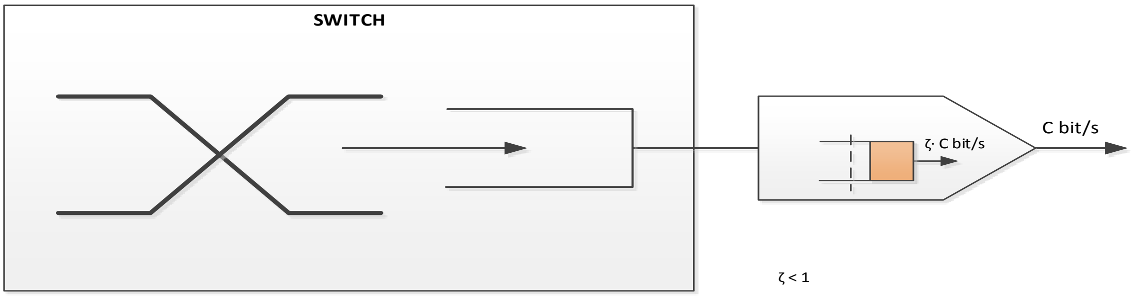


Figure 5-27 Virtual Queue

Associated to the use of virtual queues, congestion control mechanisms for data centres also incorporate hardware based packet pacing. Packet pacers are intended to deal with bursty traffic that causes spikes in queuing, increasing latency. Pacers are usually implemented as a simple leaky bucket with a configurable exit rate. In the case of the iTN, they should be present when the bit rate of the ingress port is higher the bit rate of the egress port.

It should be noticed that the implementation of these mechanisms is not cost-free, but implies a reduction of the available bandwidth. Estimations available in the literature indicate that a decrease of the order of 10-15% in the bandwidth (with respect to the use of conventional congestion mechanisms) can be expected.

CT operation

The CT is implemented by means of two components:

- The hardware based mechanism that implements the congestion control actions and that necessarily resides in the iTN.
- The software in charge of the configuration and the control of the behaviour of the hardware component.

Although both components may be physically collocated in the iTN, the working assumption is that the software module will be deployed in a separate control plane entity, like the iNC. This physical separation requires that a communication protocol should be implemented, which allows for the control of the hardware part by the control entity. It is considered that OpenFlow

The hardware component, which resides in the iTN, implements the following functionalities:

- Flows classifier.
- Flows pacers. There should be one pacer per egress port.
- Virtual egress queues. There should be a virtual queue per egress port.
- Egress flows marker
- Egress flows dropper

In order to tune the congestion control mechanism performance there are several parameters that can be used:

- Pacer exit rate: this parameter is used to evenly space the transmission of information blocks towards the egress port, so they are not sent in a burst. The pacer rate should be close to the link rate at the egress port
- Virtual queue threshold: this parameter establishes when the traffic should be marked for congestion.
- Virtual queue link utilisation factor ζ: this parameter should always be smaller than 1 and controls the rate of emptying of the virtual queue.

It should be noticed that the protection of information flows associated to functional splits that happen before the separation between cell based processing and UE based processing should be a priority, as any loss would affect to all the connections of the cell.

The virtual queue mission is to keep the egress queue empty or close to empty most of the time. This would be a simple task if the all information flows would have a continuous bit rate and a fixed inter-arrival period, as is the case for some functional splits – only incast congestion problems would need to be addressed, which are considered in the next section. But here are information flows associated to other functional splits that may exhibit variations both in the data volume and the time of arrival of the information blocks.

In the following figure an example of this latter situation is represented:

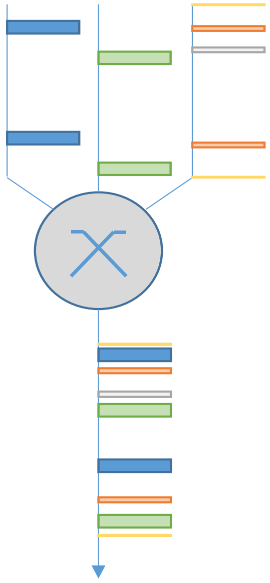


Figure 5-28 Flows Example

Blue and green blocks represent fixed high bit rate information flows, while the other represents variable bit rate flows.

As a first step, the control component of the CT (which is part of the RAC functional module in the iNC, as will be explained in section 5.5.1) establishes the configuration of the congestion control procedure to be implemented based on the characteristics of the flows that are processed by the switch.

When a packet arrives to an ingress flow, it is firstly classified, so they can distinguish which one should be introduced in the virtual queue and which ones not. This distinction is expected to happen based on the IEEE 802.1ad QinQ tag assumed to be used to route different flows in the iJOIN backhaul network. The size of the packets of the flows that should be computed in the virtual queue are computed and provided to the virtual queue mechanism.

Packets that should not be considered in the virtual queue may go through the flow pacers in order to cope with different bit rates in the ingress and egress ports. The mechanism proposed is based on the concept of leaky bucket, but in any case it is not mandatory.

The virtual egress queue simulates queue build-up for a virtual link running at a speed less that is calculated subtracting to the egress port speed the sum of the speeds of the flows that have continuous bit rate, and then applied the correction factor in the virtual egress port speed. Obviously, the virtual queue operates without buffering anything.

The virtual queue can be marked with several thresholds associated with different correcting actions for different flows or flow types. The software control module is in charge of the establishment of the correspondence between actions and thresholds. The thresholds should be associated with the latency tolerances of the flows that require continuous bit rate, and not to those that are considered in the virtual queue.

The iNC, on top of reconfiguring the congestion control parameters in the iTNs, may also request the RANaaS entity to initiate some actions to overcome the congestion situation:

- Marking IP headers of information flows as congested, before they enter the S1 interface or when they are received from the S-GW. Then the PCRF takes care of shaping traffic in order to decrease congestion.
- Change the functional split of selected information flow(s), in order to reduce their bit rates.

Incast issues

One of the problems that the iTN may face is the possibility of incast congestion for some functional split flows. Incast congestion happens in high-bandwidth and low-latency networks, when multiple synchronised servers send data to a same receiver in parallel. In the case of the iJOIN architecture, incast congestion may happen in the uplink when several iSCs transmit large blocks of information simultaneously. This situation may be generated by the support of CoMP techniques that require time synchronisation, like Joint Processing.

It should be noticed that the access control mechanism should ensure that traffic volume of the information flows does not exceed the capacity of the egress link. So the main issue to solve is to ensure that the latency limits for the flows are not exceeded.

Interaction between congestion control and admission control

One of the issues that need to be addressed is the potential interaction between the congestion control mechanisms and the admission control when a new information flow enters the network. The admission control in this case refers only to the backhaul network, i.e., it is understood as the possibility of routing a new information flow through a given iTN. The decision is taken by the iNC and in the case that the resources in the iTN are not enough to attend the new flow it can take one of three possible options:

- The new information flow is rejected and a new transport path is selected (if feasible).
- The information flow configuration is changed, e.g., applying a different functional split or changing the QoS of the connection).
- The configuration of the already served information flows is changed in order to accommodate the new one. This may be changing the functional split or even changing the transmission path for selected information flows.

Any of these options (or others not yet identified) should be activated only after the new connection has been admitted in the network, i.e., it has not been rejected either by the core network or the radio access network (or the RANaaS entity)[6].

Congestion correction actions

There are three correction actions that can be implemented by the CT in order to overcome congestion situations. In this sense, it is important to understand that in most of the cases (the exception would be when there are no flows associated with cell-based processing level functional splits), there are no real congestion situations, but virtual ones.

Marking of packets

Marking can be based on IP level Explicit Congestion Notifications (ECN) mechanisms or in new lower layer congestion notification protocols. As the former usually operate at a larger time scale, they cannot be used for solving short term congestion issues if the transport delay is significant.

Existing ECN mechanism are based on the in-band signalling of congestion. All packets on a connection have a bit set in the IP header that tells the routers that this packet belongs to a connection that understands, and will react to, ECN. Each router may use its own policy to implement the ECN mechanism, e.g., marking the packet by setting another bit in the IP header when the average queue size exceeds some threshold. Upon receiving any packet with ECN set on it, the receiver echoes this information in its ACK (or equivalent feedback) message to the sender. When the sender receives an ACK or feedback message with ECN echoed, it takes appropriate congestion control measures; e.g., by reducing its window. It also sets some information in the IP header that tells the receiver that the sender has in fact reacted to this echo.

In the context of 3GPP networks, the element in charge of reacting to the congestion notification is the Policy and Charging Rules Function (PCRF), which dynamically controls and manages all data sessions. The PCRF provides policies for congestion mitigation to one or more of the following network entities:

[6] Except for the case of a new iSC being activated.

- to the PCEF (Policy and Charging Enforcement Function) over the Gx interface;
- to the TDF (Traffic Detection Function) over the Sd interface;
- to the AF (Application Function) over the Rx interface.

Another option is the use of the Quantized Congestion Notification (QCN) algorithm, which was standardized by the DCB Task Group in March 2010 as the IEEE 802.1Qau Congestion Notification standard. QCN is a Layer 2 congestion control mechanism in which a congested switch can control the rates of Layer 2 sources (Ethernet Network Interface Cards) whose packets are passing through the switch. The algorithm essentially specifies a congestion control loop at Layer 2 similar to the TCP/RED (or DCTCP) control loops at Layer 3.

Dropping of packets

A second strategy to deal with congestion would consist in the dropping of packets from the egress port queue from selected flows. The mechanism would drop packets randomly according to a drop probability, p, which is obtained from a “drop probability calculation” component implemented in the control module of the CT. The advantage of this strategy is that, on top of activating the end-to-end congestion control mechanisms of TCP (e.g., reducing the transmission window), it allows for a direct decrease of the latency. It is also more effective when there is a high percentage of UDP based flows. The main drawback is the negative impact it may have of the QoE of the flows affected.

Changes of functional split

An additional congestion correcting mechanism is the solicitation of a change of the functional split implemented, so a lower bit rate one is used. The entity in charge of controlling the functional split used is the RANaaS, and a requisite is for the iSC to support the proposed one. On top of this, there is the issue of whether and how such a change can be implemented in an operational network.

It should be noticed that other traditional mechanism to alleviate congestion, like moving users to a different cell or changing the anchor point are not considered here. This is because the implementation of these mechanisms requires knowledge of the radio interface situation for each UE, so only those that are at the cell edge may be forced to handover to a different cell, for example. However, the control part of the CT can request other functional modules, like those in charge of load balancing and IP anchoring, to activate these mechanisms in case the congestion control procedures provided are not enough for the congestion to decrease to acceptable levels. The way this coordination between functional modules would cooperate is explained in section 5.5.1.

5.5 CT4.5: Network Wide Scheduling and Load Balancing

5.5.1 Scenario

This CT is about the load balancing and scheduling of the traffic. The main aim of Load Balancing is to distribute evenly the traffic, through the (iSC and iTN) nodes, whereas the main objective of scheduling is to allocate optimally the resources of each one of the iJOIN elements, based on queuing and smart priority algorithms. When no alternative resources exist to balance, scheduling and priority queuing are the main tools. Otherwise, load balancing and scheduling will be used jointly.

As we have already discussed, the goal of this CT is to distribute evenly the traffic over iJOIN elements (network perspective) in order to improve the performance and pre-empt congestion by taking into account the complete end-to-end (E2E) path, in a SDN-oriented environment. In addition, we should investigate the trade-off between the network-perspective in which the load is balanced equivalently, and the user-perspective in which we consider the user point-of-view (e.g., highest transmission rate). These two point-of-views can be opposed, as we analyse this trade-off below. The key point here is that the iNC decides how the overall (traffic) load should be distributed along different (alternative) elements, taking into consideration iSC and iTN nodes, and the two different perspectives.

This CT is relevant to the iJOIN architecture since it aims to provide a recommendation for the distribution of the traffic between the iJOIN elements. The main objective is to increase the use QoS, and potential interactions, e.g. with energy optimization are going to be considered.

5.5.2 Approach

In this CT, we consider both the cost of user-association and the cost of flow split in the flow-level performance. Our aim is to minimise the system cost function given below, by considering both the user QoS (e.g., physical capacity) and the cell load. In doing this, we have to find we formulate our optimisation problem as it follows

$$\Phi(\alpha) = \theta \sum_i \frac{(1-\rho 1)^{1-\alpha}}{\alpha-1} + (1-\theta) \sum_i \frac{(1-\rho 2)^{-\alpha}}{\alpha},$$

where $\Phi(\alpha)$ is the cost function that we want to minimise. For different values of α, the function changes objective. The variables $\rho 1$ and $\rho 2$ denote the average utilisation of the BS as regards its dedicated and best-effort resources, and are easily estimated using queuing theory tools.

We extended the adopted generalised α-optimal performance function in order to capture the following trade-offs:

- User versus Network perspective: the user perspective is usually associated with the BS that offers the best user QoS, e.g., the maximum physical capacity, or the lowest blocking probability. This may be contrary to the network's perspective where the emphasis is placed on equalising the loads among the BSs. This trade-off is captured by the parameter α. An example is presented in the following figure. Let us consider the user marked with the blue circle. He can be attached to either the right or the below BSs. On the one hand, if he attaches to the below BS that is quite close, he can “catch” a high transmission rate (user perspective); however, this will not enhance the network perspective, since this BS is quite busy, and thus, probably the BS will be congested. On the other hand, if we attach this user to the right BS, the network perspective will be enhanced (since the BS is quite empty), but the user will experience low transmission rate.

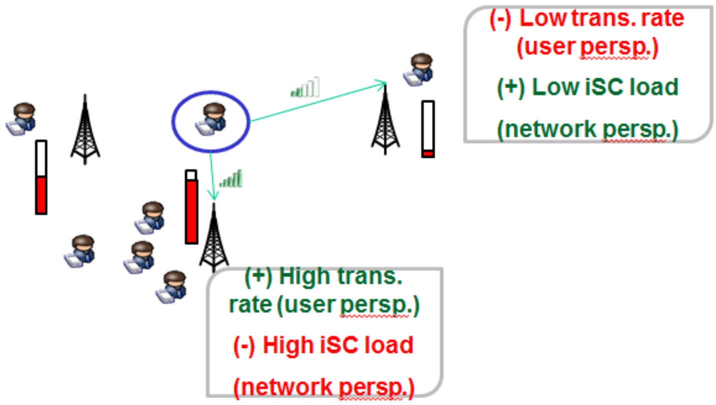


Figure 5-29 User versus Network Perspective

- Dedicated versus best-effort flows: Assuming that each iSC has two different independent utilisations, each one for the dedicated and best-effort flows, a couple of considerations arise. For example, while balancing the load we should take into account the following potential trade-off: how should we distribute both loads simultaneously optimally. This trade-off is captured from the parameter θ.

We illustrate here the optimal solutions for $\theta = 1$ and $\theta = 0$. We will explore intermediate values of θ in the next deliverable.

Here, we illustrate the optimal solution of this problem for $\theta = 1$ (pure best-effort flows approach). Each UE is associated with the j-th BS that satisfies the following equation:

$$\Phi(1) = argmax_j c_j (1-\rho 1)^{\alpha}$$

Due to the above equation, the UE selects the BS that provides the highest capacity weighted by a power of BS's idle time. By a BS's idle time we refer to the fraction of time it is inactive, i.e. $1 - \rho 1$, the system traverses between the user perspective ($\alpha = 0$), and network perspective ($\alpha \rightarrow \infty$). To put it differently, for

$\alpha = 0$, the decision is purely based on user's perceptive, i.e. based on the physical capacity (or SINR) and ignores the network traffic condition. Also, it can be shown that for $\alpha = 2$ the average delay of the system is minimized. Finally, as α further increases, the rule is such that more emphasis is placed on the traffic loads rather than the physical capacity. As $\alpha \rightarrow \infty$ the rule is such that the utilisation of all the BSs is equalized.

Now, we illustrate the optimal solution of this problem for $\theta = 0$ (pure dedicated flows approach). Each UE is associated with the j-th BS that satisfies the following equation

$$\Phi(0) \ = \ argmax_j K_j (1 - \rho 2)^{\alpha+1} = \ K_j (1 - \rho 2)^{\alpha+1}$$

Where k_j denotes the average amount of dedicated flows that the BS can handle during the next time time-period.

As for the above equation the UE selects the BS that provides the highest number of available dedicated flows-slots (i.e. the lowest blocking probability) weighted by a power of BS's idle time. To be more precise, the system traverses between the user perspective ($\alpha = 0$), and network perspective ($\alpha \rightarrow \infty$). Furthermore, for $\alpha = 0$, the decision is purely based on user's perceptive, i.e. based on blocking probability and ignores the network traffic condition. Finally, as α further increases, the rule is such that more emphasis is placed on the traffic loads rather than the blocking probability. As $\alpha \rightarrow \infty$ the rule is such that the utilisation of all the BSs is equalised.

6 Functional Architecture

In this section we describe the interactions among all modules defined in WP4, particularly within iNC. An initial description of the proposed functional architecture was provided in D4.1 [5], which is expanded and detailed in this section.

6.1 Overview

WP4 deals with the network layer functions to support the joint optimisation of RAN/backhaul transmission and the flexible functional split. In detail, several network wide mechanisms including mobility management, energy optimisation, load balancing and congestion control in RAN and backhaul network are introduced to embody the RANaaS concept. The functional architecture is illustrated in Figure 6-1, where the Software Defined Network (SDN) approach is adopted to configure, monitor and drive the operation of the RAN and backhaul network entities by the iNC.

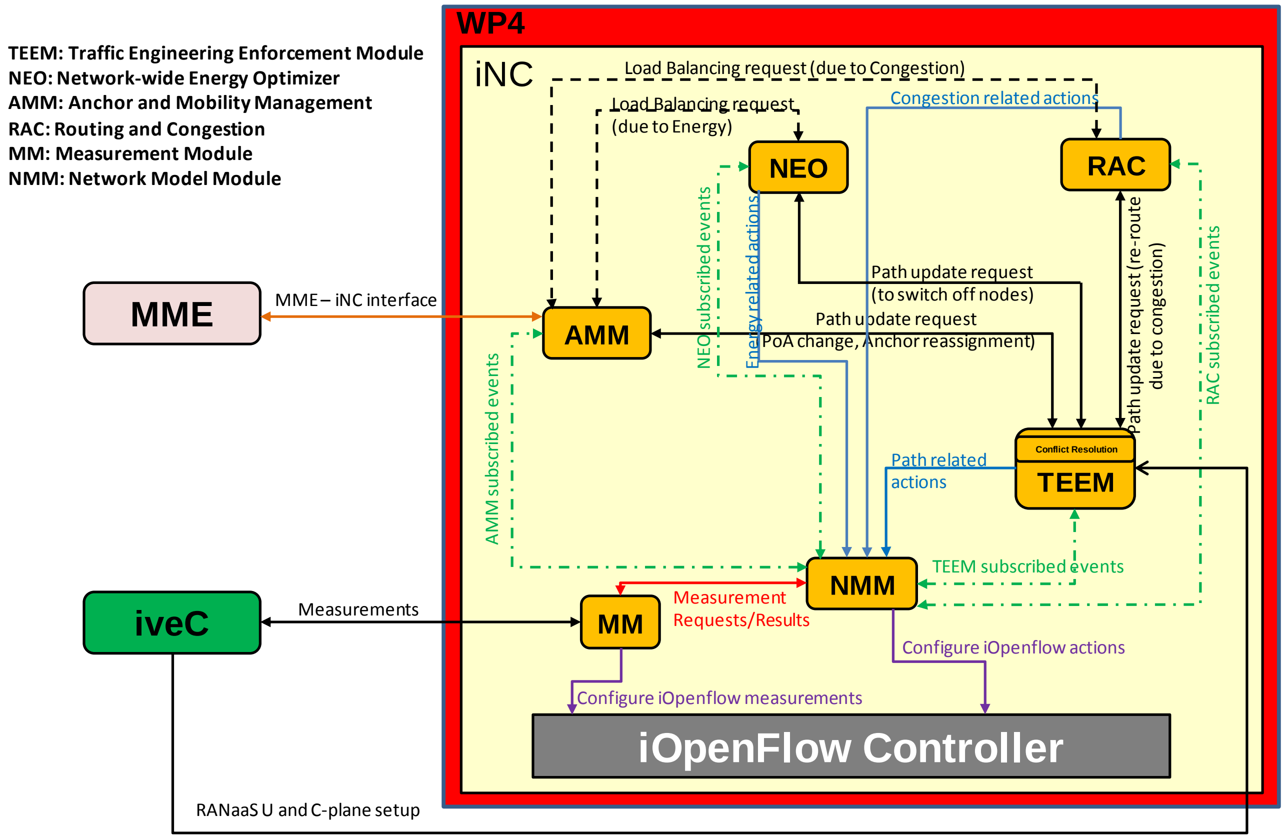


Figure 6-1 WP4 functional architecture

The iNC is a key network entity in the iJOIN architecture and it was designed as a composition of several modules. Each module is responsible for a specific mechanism and communicates with the other modules in order to accomplish a specific task. Figure 6-1 depicts the required interactions among them within the iNC as well as the interaction required with the Mobility Management Entity (MME) and the iJOIN virtual eNodeB Controler (iveC).

The definition of the functional modules follows the structure adopted for WP4 CTs. In general, there is a one-to-one mapping between the WP4 CTs and the functional modules. It can be observed that there are more modules than CTs since these additional modules, such as MM and NMM, are mainly passive. In fact, they don't take any decisions regarding the network operation but are essential for performing CTs. The main modules inside the iNC are:

- Network Model Module (NMM): This module plays a very important role as it is in charge of initially acquiring a topological and functional view of the network, i.e., which nodes are up and running and how they are interconnected, as well as which capabilities they have, for example, in terms of energy configurability of IP anchoring support. It builds a model of the network that reflects the status and that is kept up-to-date by continuously monitoring the status and load.

- Anchor and Mobility Management (AMM). This module implements most of the functionality of CT4.1, namely the selection of the proper anchors on a per-application and UE basis, as well as ensuring that those sessions needing mobility support are provided with it. Note that CT 4.1 is in charge not only of providing mobility support on an address (application) basis, but also to ensure that resources are optimally exploited, both in the backhaul and in the access. This is achieved by selecting and using an anchor closer to the UE. This does not mean that for some flows legacy EPS Rel-10 mobility mechanisms (and anchors, i.e., the PGW) are not used but that they are actually complemented by the iJOIN solutions. Although it is not shown in the figure, there might also be some AMM functionality on the UE for the case of non SDN-enabled iJOIN enhanced UEs, so the overall performance is improved.
- Network-wide Energy Optimiser (NEO). This module, defined by the CT 4.2, monitors the network status and load, and runs different algorithms to optimise the overall energy consumption while ensuring that the network wide performance is not compromised. The module is in charge of taking network wide decisions about switching on/off physical nodes, as well as ensuring that UE traffic is still properly routed by the nodes that are running at each time.
- Routing and Congestion (RAC). This module, partially defined by the CT 4.4, is in charge of avoiding network congestion in the RAN/backhaul, by properly configuring the network and requesting changes on the paths used by active data flows. In order to do so, both the status of the RAN and the UE traffic requirements are considered.
- Traffic Engineering Enforcement Module (TEEM). This module, defined by CT4.3, is a key WP4 module that hosts all the intelligence required to compute the best path within the backhaul to support the different traffic and network-wide requirements, providing the necessary conflict resolution functions (e.g., to ensure that a request from the NEO module does not introduce congestion or contradicts a previous request from the RAC module).
- Measurement Module (MM). This module is in charge of configuring the iOpenFlow controller to perform the required measurements. These measurements might be dynamically requested by both the WP4 modules as well as WP2/WP3, and therefore has intra- and inter-WP interfaces. Envisioned metrics to be reported by the MM comprise: locally experienced congestion, available neighbours, available data rates, and number of connected UEs. The MM will support several reporting modes, e.g., asynchronous, periodic or event based.
- iOpenFlow Controller (iOpenFlow Controller). The extended OpenFlow controller is a critical entity located at the iNC, taking care of all the protocol interactions with the rest of the WP4 network entities which only need to support OpenFlow, using the so-called Southbound protocol interface.

The communication between the modules follows an event-driven communication paradigm. Therefore, each module exports the required events making available the subscription to other modules that are interested in such events. The event-driven approach brings two main advantages:

1. Increased responsiveness compared to an asynchronous communication paradigm. Indeed, event-driven systems are, by design, more normalised to unpredictable and asynchronous environments. In the case of the iJOIN architecture, the communication between the modules is intrinsically asynchronous and unpredictable.
2. An event-driven architecture can be used as complement of a service-oriented architecture because services can be activated by triggers fired on incoming events. Service-oriented architectures are a software design and software architecture design pattern based on discrete pieces of software providing application functionality as services to other applications. This is the case of the whole iJOIN functional architecture where the modules provide different services to other modules, i.e., the Path Computation service offered by TEEM module.

6.2 Module specification: Interaction of WP4 Modules

The network entity of iNC has the required intelligence to ensure that both RAN and backhaul network will operate with the required performance. Given the implemented SDN approach, the functionality associated with each CT is actually not provided just by the respective module, but it often requires the participation of several modules. Thus, in order to fulfil one triggered procedure, several or all of the WP4 modules should interact with each other according to algorithms and mechanisms designed introduced by each CT.

Most of the interactions occur between two modules. In this case the event driven communication does not introduce any sort of inconsistence since all the processing and communication is managed by the two modules. Contrarily, when a complex operation involves multiple modules, iNC requires an additional mechanism to ensure the system's integrity. This mechanism is based on transaction processing which is designed to maintain a system's integrity in a known, consistent state, by ensuring that interdependent operations on the system are either all completed successfully or all cancelled successfully. Transaction processing links multiple individual operations in a single, indivisible transaction, and ensures that either all operations in a transaction are completed without error, or none of them are. If some of the operations are completed but errors occur when the others are attempted, the transaction-processing system "rolls back" all of the operations of the transaction (including the successful ones), thereby erasing all traces of the transaction and restoring the system to the consistent, known state that it was in before processing of the transaction began.

If all operations of a transaction are completed successfully, the transaction is committed by the system, and all changes are made permanent. The transaction cannot be rolled back once this is done. This behaviour is formalised by ACID properties (Atomicity, Consistency, Isolation, and Durability) that guarantee that transactions are processed reliably. Atomicity requires each transaction to be "all or nothing": if one part of the transaction fails, the entire transaction fails, and the system state is left unchanged. The consistency property ensures that any transaction will bring the system from one valid state to another. The isolation property ensures that the concurrent execution of transactions results in a system state that would be obtained if transactions were executed serially. Durability means that once a transaction has been committed, it will remain so, even in case of errors. Since iJOIN functional architecture can be seen as a distributed system, atomicity must be ensured for distributed transactions. The two-phase commit protocol provides atomicity in such case. Each participant in the transaction agrees on whether the transaction should be committed or not. Briefly, in the first phase, one module (the coordinator) interrogates the other modules (the participants) and only when all reply that they are prepared does the coordinator, in the second phase, formalise the transaction. For the sake of brevity, from now on the term transaction refers to the aforementioned mechanism including all its properties.

In the following subsections the detailed interaction of modules will be discussed with each module. Our goal at this stage is not to be exhaustive on the detailed design, but rather illustrative on the approach that will be followed for the iNC implementation.

6.2.1 Network Model Module (NMM)

6.2.1.1 Function overview

This module plays a very important role as it is in charge of initially acquiring a topological and functional view of the network, i.e., which nodes are up and running and how they are interconnected, as well as which model of the network that reflects the status and that is kept up-to-date by continuously monitoring the status and load.

6.2.1.2 Interactions with other modules

Since all other modules in WP4 will interact with NMM module, the detailed information on these interactions can be found in the following sections.

NMM–MM

1. When NMM requires a measurement, it sends the request to MN in a 2-tuple message. Such message contains the network node ID, the measurement rule (e.g. periodic interval, per-flow counter etc.)

   (network-node#ID; measurement-rule)

   Whenever MM collects a measurement requested by NMM, it will send the result to NMM. The structure of such message is defined in Section 6.2.6.2.

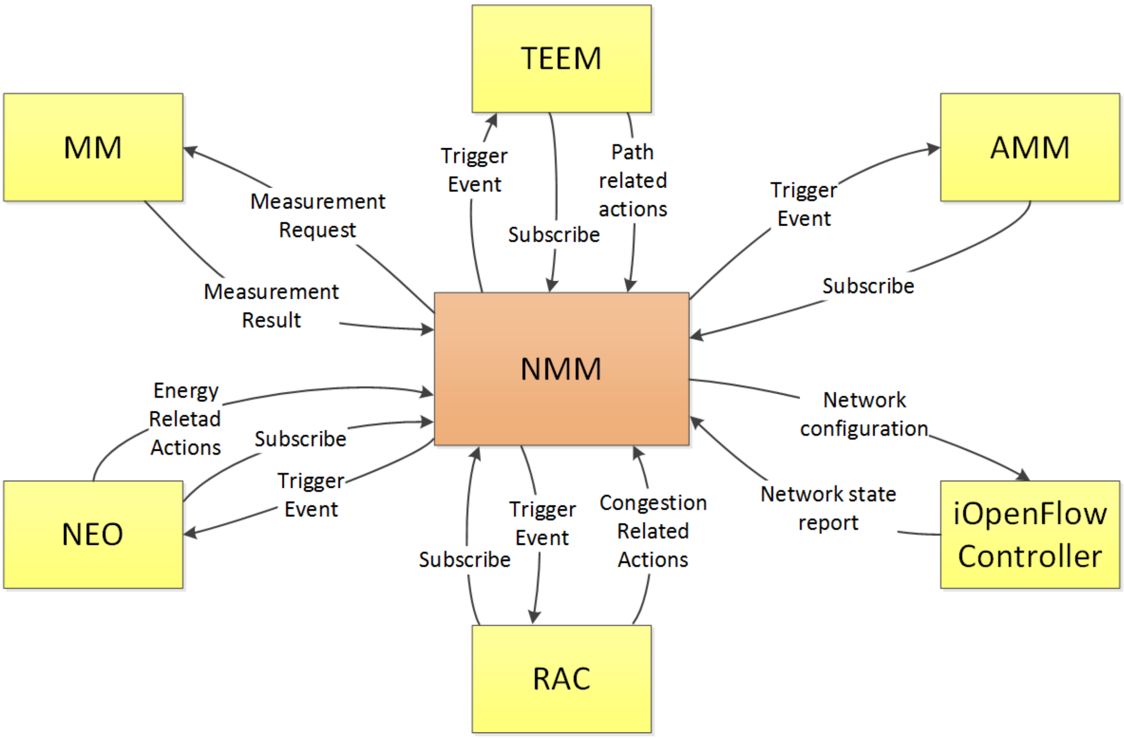


Figure 6-2 Interaction of NMM module

NMM-TEEM

1. When NMM receives a "*Get-network-snapshot*" message from TEEM (see Section 6.2.5.2), it replies with an *N*-tuple message, where *N* is the number of nodes in the network. Each element represents a network node with all its attributes.

   (network-node#ID1; network-node#ID2; …; network-node#ID*N*)

2. If TEEM is subscribed to NMM regarding some changes in the network, NMM will trigger TEEM module whenever the related information is updated. NMM sends a 2-tuple message which contains the network node with all its attributes, and the type of event. The possible events are: a new node has been added to the network (ADD), a node has been removed from the network (DEL), the attributes of a node have changed (UPDATE).

   (network-node#ID; type-of-event)

NMM-AMM

1. When NMM receives a "*Get-network-snapshot*" message from AMM (see Section 6.2.2.2), it replies with an *N*-tuple message, where *N* is the number of nodes in the network. Each element represents a network node with all its attributes.

   (network-node#ID1; network-node#ID2; …; network-node#ID*N*)

2. If AMM is subscribed to NMM regarding some changes in the network, NMM will trigger AMM module whenever the related information is updated. NMM sends a 2-tuple message which contains the network node with all its attributes, and the type of event. The possible events are: a new node has been added to the network (ADD), a node has been removed from the network (DEL), the attributes of a node have changed (UPDATE).

   (network-node#ID; type-of-event)

NMM-NEO

1. When NMM receives a "*Get-network-snapshot*" message from NEO (see Section 6.2.3.2), it replies with an *N*-tuple message, where *N* is the number of nodes in the network. Each element represents a network node with all its attributes.

   (network-node#ID1; network-node#ID2; …; network-node#ID*N*)

2. If AMM is subscribed to NMM regarding some changes in the network, NMM will trigger NEO module whenever the related information is updated. NMM sends a 2-tuple message which contains the network node with all its attributes, and the type of event. The possible events are: a new node has been added to the network (ADD), a node has been removed from the network (DEL), the attributes of a node have changed (UPDATE).

   (network-node#ID; type-of-event)

3. When NEO decides to switch on/off a network's node, it invites NMM to join the common transaction. NMM acknowledges NEO for taking part of the transaction with a 3-tuple message containing the Transaction#ID, the type of event, and an explicit ACK.

   (Transaction#ID; type-of-event; ACK)

4. When NEO asks NMM to switch on or off physical nodes such as iSC and iTN, NMM will try to address the request through iOpenFlow Controller. NMM will acknowledge NEO with a 3-tuple message containing the network-node#ID, the type of operation, and an explicit ACK or NACK depending on the result of the operation.

   (network-node#ID; type-of-operation; ACK | NACK)

NMM-RAC

1. When NMM receives a "*Get-network-snapshot*" message from RAC (see Section 6.2.4.2), it replies with an *N*-tuple message, where *N* is the number of nodes in the network. Each element represents a network node with all its attributes.

   (network-node#ID1; network-node#ID2; …; network-node#ID*N*)

2. If RAC is subscribed to NMM regarding some changes in the network, NMM will trigger RAC module whenever the related information is updated. NMM sends a 2-tuple message which contains the network node with all its attributes, and the type of event. The possible events are: a new node has been added to the network (ADD), a node has been removed from the network (DEL), the attributes of a node have changed (UPDATE).

   (network-node#ID; type-of-event)

3. When RAC decides to update the congestion control parameters on an iSC or iTN, it invites NMM to join the common transaction. NMM acknowledges RAC for taking part of the transaction with a 3-tuple message containing the Transaction#ID, the type of event, and an explicit ACK.

   (Transaction#ID; type-of-event; ACK)

4. When RAC module asks NMM to update the congestion control parameters on an iSC or iTN, NMM will try to address the request through iOpenFlow Controller. NMM will acknowledge NEO with a 3-tuple message containing the direction, the port ID with related parameters and an explicit ACK or NACK depending on the result of the operation.

   (network-node#ID; Direction (UL/DL); Port#ID [Module #ID, NewValue], ACK | NACK)

5. Whenever the congestion threshold is reached in an iTN (see Section 6.2.4.2), NMM send to RAC an *N*-tuple message containing the network node's ID, the measurement's Timestamp, the direction of the controlled flows, the egress port that will be modified and the specific functional module of the iTN/iSC mechanism

   (network-node#ID; Timestamp; Direction (UL/DL); Port#ID [Module #ID, Value])

6.2.2 Anchor and Mobility Management (AMM)

6.2.2.1 Function overview

This module implements most of the functionality related to mobility management, namely the selection of the proper anchors on a per application and UE basis, as well as ensuring that those sessions needing mobility support are provided with it.

6.2.2.2 Interactions with other modules

The interaction with AMM module is shown in Figure 6-3. AMM, for properly work within the iNC, has to interact with TEEM, NMM, NEO and RAC modules. In addition to this AMM interacts also with the external Mobility Management Entity (namely MME) which is defined in 3GPP standard [1] via interface J4. In the following each interaction is detailed.

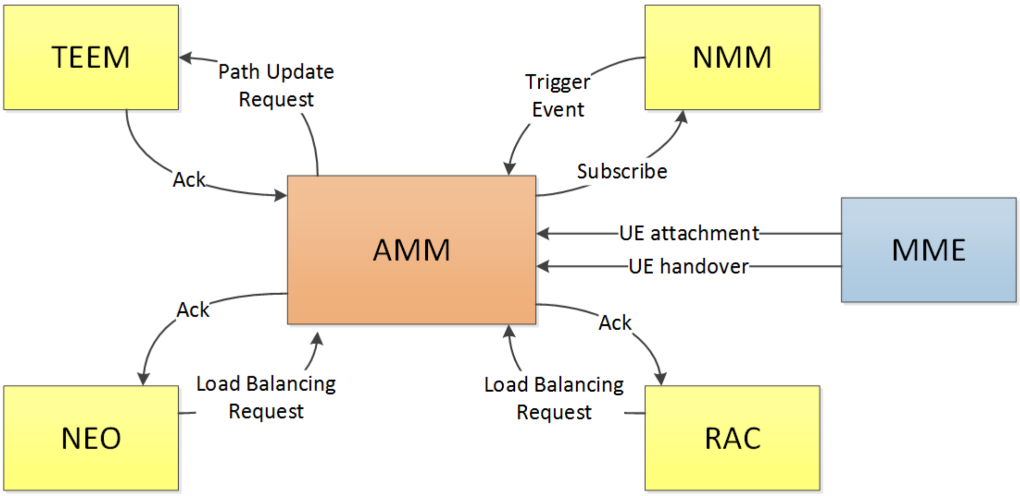


Figure 6-3 Interaction of AMM module

AMM-MME

1. When an UE attaches to the network, MME communicates to AMM the attachment through a 3-tuple message. Such message contains the UE's ID, the veNB's ID where the UE is attached, and the PDN connection's ID.

   (UE#ID, veNB#ID, PDN#ID)

   AMM does not reply with any message to MME since no further interaction is required between the two modules.

2. When an UE performs a handover, MME communicates to AMM the handover through a 4-tuple message. Such message contains the UE's ID, the veNB's ID where the UE is currently attached, the PDN connection's ID, and the veNB's ID where the UE was previously attached.

   (UE#ID, veNB-new#ID, PDN#ID, veNB-old#ID)

   AMM does not reply with any message to MME since no further interaction is required between the two modules.

AMM-NMM

1. When AMM is executed for the first time, it sends to NMM a 1-tuple message in order to get the topological and functional view of the network. The message contains the requests of retrieving a complete snapshot of the network.

   (Get-network-snapshot)

   The response message is defined in Section 6.2.1.2.

2. In order to keep updated the view of the network, AMM subscribes to NMM through a 2-tuple message. Such message contains the scope of the message (subscription) and the required subscription (changes in the network).

   (subscription, network-changes)

   The response message is defined in Section 6.2.5.2.

AMM-TEEM

1. Upon UE's attachment, AMM selects a pool of possible anchors for the UE. The following step is requiring the TEEM to configure a path between the veNB where the UE is attached, and the

selected anchors. AMM sends to TEEM the UE's ID, the veNB's ID, and a list of selected anchor IDs in a 3-tuple message. The anchors' list is sorted in order of preference.

(UE#ID, veNB#ID, [Anchor#ID1, Anchor#ID2, …])

Upon the reception of this message, TEEM starts to check if the required paths can be configured or not. If TEEM returns an empty list (see Section 6.2.5.2), AMM has to re-choose the anchors to be assigned to the UE.

2. When an UE performs a handover and AMM decides to keep the same anchors previously assigned (intra-anchor handover), AMM sends to TEMM a 4-tuple message. Such message contains the UE's ID, the new veNB's ID, the list of previously assigned anchor IDs, and the old veNB's ID. Also in this case the anchors list is sorted in order of preference.

   (UE#ID, veNB-new#ID, [Anchor#ID1, Anchor#ID2, …], veNB-old#ID)

   Upon the reception of this message, TEEM starts to check if the required paths can be configured or not. If TEEM returns an empty list (see Section 6.2.5.2), AMM has to re-choose the anchors to be assigned to the UE. This means that, even if AMM does not consider appropriate to change the anchors, TEEM is not able to configure the required path and a new anchor selection has to be performed.

3. When an UE performs a handover and AMM decides to change the anchors previously assigned (inter-anchor handover), AMM sends to TEMM a 5-tuple message. Such message contains the UE's ID, the new veNB's ID, the new pool of anchors sorted in order of preference, and the old veNB's ID, and the list of previously assigned anchor IDs.

   (UE#ID, veNB-new#ID, [An-new#ID1, An-new#ID2, …],
   veNB-old#ID, [An-old#ID1, An-old#ID2, …])

   Upon the reception of this message, TEEM starts to check if the required paths can be configured or not. If TEEM returns an empty list (see Section 6.2.5.2), AMM has to re-choose the anchors to be assigned to the UE.

AMM-NEO

1. When NEO decides to switch on/off a network's node (see Section 6.2.3.2), it invites AMM to join the common transaction. AMM acknowledges NEO for taking part of the transaction with a 3-tuple message containing the Transaction#ID, the type of event, and an explicit ACK.

   (Transaction#ID, type-of-event, ACK)

2. When NEO module decides to switch on/off an iTN (see Section 6.2.3.2), AMM is asked to check whether it is possible to reassign the UEs' anchors. AMM interacts with TEEM to check the feasibility of path updating. If the new path can be configured, AMM sends back to NEO an Acknowledgment message with UE related information whose path is expected to be updated.

   (network-node#ID, type-of-operation, ACK, [(UE#ID1, veNB#ID1, Anchor#ID1),
   (UE#ID2, veNB#ID2, Anchor#ID2), …])

   Contrarily, if the new path cannot be configured, AMM sends back to NEO a Not Acknowledgment message.

   (network-node#ID, type-of-operation, NACK)

   In case of switch-on, AMM always sends back to NEO an Acknowledgment message.

   (network-node#ID, type-of-operation, ACK, [(UE#ID1, veNB#ID1, Anchor#ID1), (UE#ID2,
   veNB#ID2, Anchor#ID2), …])

3. When NEO decides to switch off an iSC (see Section 6.2.3.2), and this iSC provides association services to one or more UEs, NEO communicates to AMM the IDs of these UEs which will be handed off to available neighbouring cells. When a UE completes the handover procedure, the AMM module will receive a message from MME and try to reassign the anchors if possible. It means that AMM has the ability to detect whether all these UEs have finished their handover procedures. Thus according to this judgment, AMM will reply to NEO with an N-tuple message, where N is the

number of users communicated by NEO. Each element of the message represents the acknowledge code for each UE. The acknowledgement list is sorted following the same order communicated by NEO.

(ACK#1, ACK#2, …, ACK#N)

AMM-RAC

1. When RAC decides to update the congestion control parameters on an iSC or iTN, it invites AMM to join the common transaction. AMM acknowledges RAC for taking part of the transaction with a 3-tuple message containing the Transaction#ID, the type of event, and an explicit ACK.

   (Transaction#ID; type-of-event; ACK)

2. When RAC module asks to AMM to check if an anchor reassignment is required (see Section 6.2.4.2), AMM interacts with TEEM (as described in points 2 and 3 of AMM-TEEM interaction). If the new path can be configured, AMM sends back to RAC an Acknowledgment message.

   (Request#ID; ACK)

   Contrarily, if the new path cannot be configured, AMM sends back to RAC a Not Acknowledgment message.

   (Request#ID; NACK)

6.2.3 Network-wide Energy Optimiser (NEO)

6.2.3.1 Function overview

This module monitors the status and the load of the network, and runs different algorithms to optimize the overall energy consumption, while ensuring that the network wide performance is not compromised. The module is in charge of taking network wide decisions about switching on/off physical nodes, as well as ensuring that UE traffic is still properly routed by the nodes that are running at each time.

6.2.3.2 Interactions with other modules

The interaction for NEO module is described in Figure 6-5. To realise the operation of network wide energy efficiency, NEO has to interact with TEEM, NMM, AMM modules.

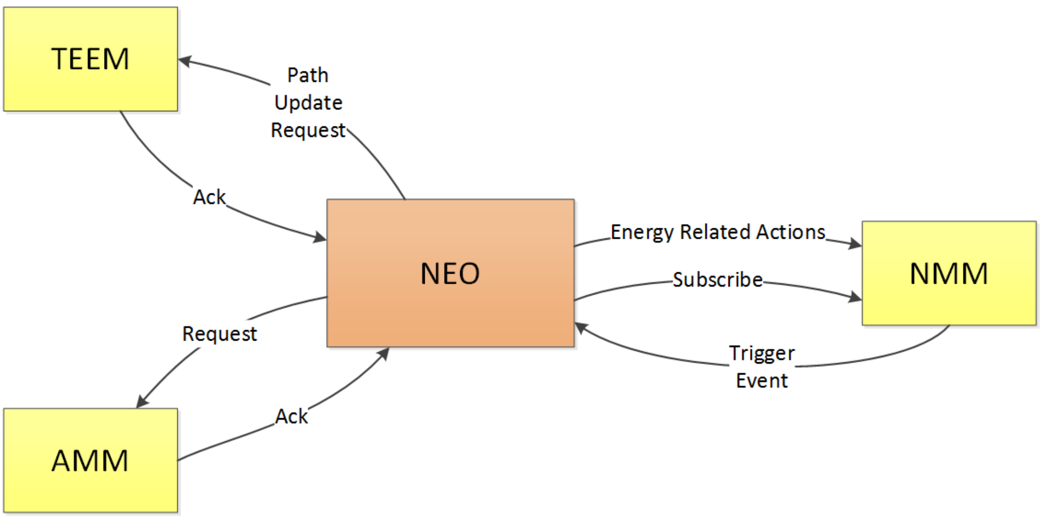


Figure 6-4 Interaction of NEO module

The whole procedure to switch on/off physical nodes is based on transaction concept since requires cooperation between AMM, NMM and TEEM modules. The procedure can be divided into four aspects, dependent on iTN or iSC, switch on or switch off.

A. Switch off iTN:
   1) NEO starts a transaction;
   2) NEO tells AMM, TEEM, NMM to be part of transaction;
   3) Network view update:

a) NEO requests NMM to update the network view with the assumption of iTN switched off;
b) NMM sends an update of network view to AMM, NEO and TEEM;
c) NMM acknowledges NEO;

4) Anchor reassignment:
a) NEO asks AMM to reassign the anchors;
b) AMM reassigns the anchors after checking the feasibility of path updating with TEEM;
c) AMM acknowledges NEO;

5) Path reconfiguration:
a) NEO asks TEEM to reconfigure the paths in the network;
b) TEEM reconfigures the path;
c) TEEM acknowledges NEO;

6) iTN switches off:
a) NEO requests NMM to switch off iTN;
b) NMM sends message down to switch off iTN;
c) NMM acknowledges NEO;

7) If (everything OK):
NEO communicates the OK transaction's end to NMM, AMM and TEEM, all the changes made so far become definitive.
Else (if something gone wrong):
NEO communicates the NO transaction's end to NMM, AMM and TEEM, All the changes made so far are reverted.

B. Switch on iTN:

1) NEO starts a transaction;
2) NEO tells AMM, TEEM, NMM to be part of transaction;
3) Network view update:
a) NEO requests NMM to update the network view with the assumption of iTN switched on;
b) NMM sends an update of network view to AMM, NEO and TEEM;
c) NMM acknowledges NEO;

4) Anchor reassignment:
a) NEO asks AMM to reassign the anchors;
b) AMM reassigns the anchors after checking the feasibility of path updating with TEEM;
c) AMM acknowledges NEO;

5) Path reconfiguration:
a) NEO asks TEEM to reconfigure the paths in the network;
b) TEEM reconfigures the path;
c) TEEM acknowledges NEO;

6) iTN switches on:
a) NEO requests NMM to switch on iTN;
b) NMM sends message down to switch on iTN;
c) NMM acknowledges NEO;

7) If (everything OK):
NEO communicates the OK transaction's end to NMM, AMM and TEEM, all the changes made so far become definitive.
Else (if something gone wrong):
NEO communicates the NO transaction's end to NMM, AMM and TEEM, all the changes made so far are reverted.

C. Switch off iSC:

1) NEO starts a transaction;
2) NEO tells AMM, TEEM, NMM to be part of transaction;
3) Network view update:

a) NEO requests NMM to update the network view with the assumption of iSC switched off;
b) NMM sends an update of network view to AMM, NEO and TEEM;
c) NMM acknowledges NEO;

4) Handover of related UEs:
a) NEO requests NMM to perform handover operations for all related UEs (no acknowledgement is needed for this request);
b) NEO also notifies AMM the UE list which is involved in this procedure;
c) NMM performs UE handover one by one (other scheme may be allowable), where the normal signalling and procedure related to handover is triggered;
d) AMM acknowledges NEO after all the handovers are completed;

6) iSC switches off:
a) NEO requests NMM to switch off iSC;
b) NMM sends message down to switch off iSC;
c) NMM acknowledges NEO;

7) If (everything OK):
NEO communicates the OK transaction's end to NMM, AMM and TEEM, all the changes made so far become definitive.
Else (if something gone wrong):
NEO communicates the NO transaction's end to NMM, AMM and TEEM, all the changes made so far are reverted, except those UEs whose handover has been finished (step 4).

D. Switch on iSC:
1) NEO starts a transaction;
2) NEO tells AMM, TEEM, NMM to be part of transaction;
3) Network view update:
a) NEO requests NMM to update the network view with the assumption of iSC switched on;
b) NMM sends an update of network view to AMM, NEO and TEEM;
c) NMM acknowledges NEO;
4) iSC switches on:
a) NEO requests NMM to switch on iSC;
b) NMM sends message down to switch on iSC;
c) NMM acknowledges NEO;
5) If everything OK:
NEO communicates the OK transaction's end to NMM, AMM and TEEM, all the changes made so far become definitive.
Else (if something gone wrong):
NEO communicates the NO transaction's end to NMM, AMM and TEEM, all the changes made so far are reverted.

NEO-NMM

1. When NEO is executed for the first time, it sends to NMM a 1-tuple message in order to get the topological and functional view of the network. The message contains the requests of retrieving a complete snapshot of the network.

   (Get-network-snapshot)

   The response message is defined in Section 6.2.1.2.

2. In order to keep updated the view of the network, NEO subscribes to NMM through a 2-tuple message. Such message contains the scope of the message (subscription) and the required subscription (changes in the network).

   (subscription; network-changes)

   The response message is defined in Section 6.2.1.2.

3. In order to keep the consistence among different modules, NEO will invite NMM module and other modules to join or exist from a common transaction, which is done by a 2-tuple message. The 2 elements including the transaction ID, type of event (join or exist).

   (Transaction#ID; type-of-event)

4. In case of iSC switch-off, NEO should firstly handover the associated UEs to available neighbouring cells before switching off the iSC. To support this, NEO will send an *N*-tuple message to NMM module, which takes the responsibility to trigger the UE handover process (maybe via RANaaS by using extended OpenFlow messages). In the *N*-tuple message, each element is a 3-tuple item, as follows:

   ((UE#ID1, iSC-old#ID1, iSC-new#ID1); (UE#ID2, iSC-old #ID2, iSC-new#ID2); …;

   (UE#IDN, iSC-old #IDN, iSC-new#IDN))

   The acknowledgment message is defined in Section 6.2.1.2.

5. In order to switch on or off physical nodes such as iSC and iTN, NEO will send a 2-tuple message to NMM module, which take the responsibility to switch on or off the physical node indicated in this message (maybe via RANaaS by using extended OpenFlow messages). This 2-tuple message contains the network node ID and the type of operation. The possible operations are: switch on and switch off.

   (network-node#ID; type-of-operation)

   The acknowledgment message is defined in Section 6.2.1.2.

NEO-AMM

1. In order to keep the consistence among different modules, NEO will invite AMM module and other modules to join or exist from a common transaction, which is done by a 2-tuple message. The 2 elements including the transaction ID, type of event (join or exist).

   (Transaction#ID; type-of-event)

   The acknowledgment message is defined in Section 6.2.2.2.

2. When NEO module decides to switch on/off an iTN, multiple related traffic flow path would or may be updated, sometimes even the anchors for some UEs will be reassigned. In this case NEO will ask to AMM to check whether it is possible to reassign the UEs' anchors. AMM receives from NEO the request through a 2-tuple message which contains the ID of network node and its related operation, i.e. switched off or on.

   (network-node#ID; type-of-operation)

   The acknowledgment message is defined in Section 6.2.2.2

3. When NEO decides to switch off an iSC, and this iSC provide association services to one or more UEs, NEO communicates to AMM these UEs which will be handed off to available neighbouring cells, through an *N*-tuple message, where *N* is the number of UEs and each element represents the UE's ID.

   (UE#ID1; UE#ID2; …; UE#IDN)

   The acknowledgment message is defined in Section 6.2.2.2

NEO-TEEM

1. In order to keep the consistence among different modules, NEO will invite TEEM module and other modules to join or exist from a common transaction, which is done by a 2-tuple message. The 2 elements including the transaction ID, type of event (join or exist).

   (Transaction#ID; type-of-event)

   The acknowledgment message is defined in Section 6.2.5.2.

2. When NEO module decides to switch on or off an iTN and acknowledged by AMM module, NEO will trigger TEEM module to reconfigure all related traffic flow paths with the assumption that this iTN is switched on or off. This trigger message from NEO to TEEM is 2-tuple one which contains the ID information of network node, its related operation, i.e. switched off or on, and the path to be updated (it is a results from AMM acknowledgement)

   (network-node#ID; type-of-operation; UE#ID; veNB#ID; Anchor#ID)

   The acknowledgment message is defined in Section 6.2.5.2. After all paths updated, NEO can truly switch on or off this iTN node by sending the correspondent message to NMM module.

6.2.4 Routing and Congestion (RAC)

6.2.4.1 Function overview

This module is in charge of avoiding network congestion in the RAN/backhaul, by properly configuring the network and requesting changes on the paths used by active data flows. These changes may be of two different kinds: moving UEs to different iSCs, so the traffic managed by the iTN decreases, or changing the configuration of the backhaul network, so less traffic goes through the congested node. It should be noticed that these correcting actions are not controlled by RAC, but by other modules defined for the functional architecture, like AMM and TEEM. The reason for adopting this approach is clear: the management of the congestion issues in the iTNs should not have precedence over the management of radio interface and the mobility.

6.2.4.2 Interactions with other modules

The interaction for RAC module is illustrated in Figure 6-5.

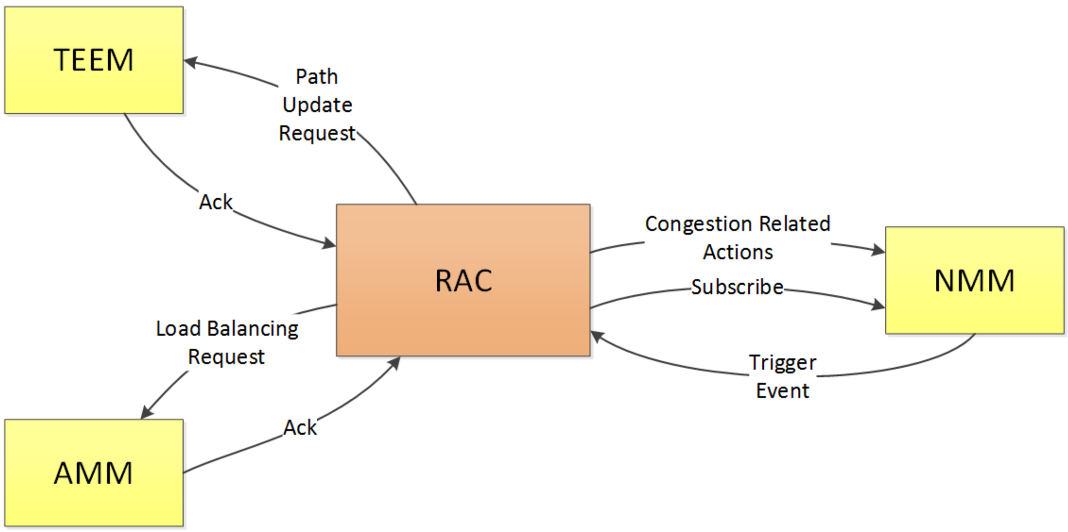


Figure 6-5 Interaction of RAC module

The load balancing procedure is based on transaction concept since requires cooperation between AMM and TEEM modules. The procedure is composed by the following steps:

A. Load balancing request:
   1) RAC starts a transaction;
   2) RAC tells AMM, TEEM to be part of transaction;
   3) RAC tells TEEM to compute new paths due congestion;
      a. TEEM acknowledges RAC;
   4) Anchor assignment:
      a) RAC asks AMM to reassign the anchors;
      b) AMM reassigns the anchors after checking the feasibility of path updating with TEEM;
      c) AMM acknowledges RAC;
   5) If (everything OK):
      NEO communicates the OK transaction's end to NMM, AMM and TEEM, all the changes made so far become definitive.

Else (if something gone wrong):

NEO communicates the NO transaction's end to NMM, AMM and TEEM, All the changes made so far are reverted.

RAC-NMM

1. When RAC is executed for the first time, it sends to NMM a 1-tuple message in order to get the topological and functional view of the network. The message contains the requests of retrieving a complete snapshot of the network.

   (Get-network-snapshot)

   The response message is defined in Section 6.2.1.2.

2. In order to keep updated the view of the network, RAC subscribes to NMM through a 2-tuple message. Such message contains the scope of the message (subscription) and the required subscription (changes in the network). For example, if a handover has happened that takes one UE flow path outside the iTN, then the RAC module should be informed in order to potentially (but not necessarily) modify the congestion control parameters.

   (subscription, network-changes)

   The response message is defined in Section 6.2.1.2.

3. RAC asks NMM to collect the status of the parameters that characterise the performance of the congestion control mechanisms implemented in the iTN. This collection will happen periodically and event driven. Periodic measurements can be used by RAC in order to tune the congestion control parameters in order to improve the overall performance. The latter case will happen when one or several of the parameters have exceeded the established threshold that identifies non solvable congestion situations. RAC sends to NMM a *N*-tuple message containing the scope of the message (subscription), the network node's ID, the direction of the flows to be controlled; the egress port that will be modified, the specific functional module of the iTN/iSC mechanism.

   (subscription; network-node#ID; Direction (UL/DL); Port#ID [Module #ID, Threshold],…)

4. If RAC module wants to update the congestion control parameters on an iSC or iTN, it will send the corresponding message to NMM module, which will be responsible to complete this through the iOpenFlow Controller.

   The request message will consist of *N*-tuple of values that identify the network node's ID, the direction of the flows to be controlled; the egress port that will be modified, the specific functional module of the iTN/iSC mechanism.

   (network-node#ID; Direction (UL/DL); Port#ID [Module #ID, NewValue],…)

   The acknowledgment message is defined in Section 6.2.1.2.

5. In order to keep the consistence among different modules, RAC will invite NMM module and other modules to join or exist from a common transaction, which is done by a 2-tuple message. The 2 elements including the transaction ID, type of event (join or exist).

   (Transaction#ID; type-of-event)

   The acknowledgment message is defined in Section 6.2.1.2.

RAC-AMM

1. In order to keep the consistence among different modules, RAC will invite AMM module and other modules to join or exist from a common transaction, which is done by a 2-tuple message. The 2 elements including the transaction ID, type of event (join or exist).

   (Transaction#ID; type-of-event)

   The acknowledgment message is defined in Section 6.2.2.2.

2. When RAC module decides to perform load balancing operation, it has to be sure that the involved UEs maintain the same QoE. At this purpose, it asks to AMM to check whether it is possible to

reassign the UEs' anchors. RAC sends to AMM the list of congested nodes in an *N*-tuple message. The message contains also a request ID.

(Request#ID; [network-node#ID1, …, network-node#ID*N*])

The acknowledgment message is defined in Section 6.2.2.2.

RAC-TEEM

1. If the congestion correction requires the establishment of a new path for some of the traffic flows that go through the iTN, then it will ask the TEEM module to compute the best one, while ensuring that there are no conflicts with other functional modules. RAC sends an *N*-tuple message, where *N* is the number of congested nodes. Such message contains several information elements, like the identification of the nodes that are congested and the congestion degree for each of them. Additional information may be provided based on the algorithm that is being used by TEEM to compute the path.

   ((network-node#ID1, congestion-level); …; (network-node#ID*N*, congestion-level))

   The acknowledgment message is defined in Section 6.2.5.2.

6.2.5 Traffic Engineering Enforcement Module (TEEM)

6.2.5.1 Function overview

This module is a key WP4 module that hosts all the intelligence required to compute the best path within the backhaul to support the different traffic and network-wide requirements, providing the necessary conflict resolution functions (e.g., to ensure that a request from the NEO module does not introduce congestion or contradicts a previous request from the RAC module).

6.2.5.2 Interactions with other modules

This module is a core function in iNC, and will be triggered by four modules, including NMM, NEO, RAC and AMM, as shown in **Errore. L'origine riferimento non è stata trovata.**. Also iveC functions may interact with TEEM module.

TEEM-NMM

1. When TEEM is executed for the first time, it sends to NMM a 1-tuple message in order to get the topological and functional view of the network. The message contains the requests of retrieving a complete snapshot of the network.

   (Get-network-snapshot)

   The response message is defined in Section 6.2.1.2.

2. In order to keep updated the view of the network, TEEM subscribes to NMM through a 2-tuple message. Such message contains the scope of the message (subscription) and the required subscription (changes in the network).

   (subscription, network-changes)

   The response message is defined in Section 6.2.1.2.

TEEM-AMM

1. Upon AMM request (see Section 6.2.2.2), TEEM tries to configure the required paths. TEEM acknowledges AMM by sending back the UE ID, the veNB ID and the list of anchors for which a path has been configured.

   (UE#ID; veNB#ID; [Anchor#ID1, Anchor#ID2, …])

   An empty anchors list means that it was not possible to configure any path and AMM has to reselect the pool of anchors.

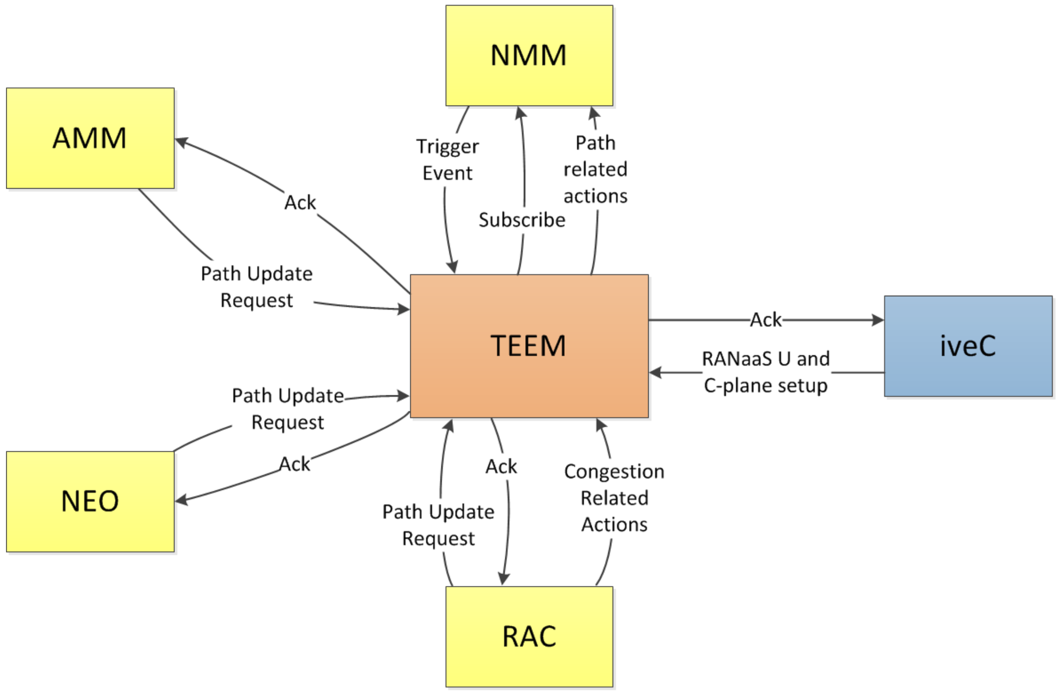


Figure 6-6 Interaction of TEEM module

TEEM-NEO

1. When NEO decides to switch on/off a network's node (see Section 6.2.3.2), it invites TEEM to join the common transaction. TEEM acknowledges NEO for taking part of the transaction with a 3-tuple message containing the Transaction ID, the type of event, and an explicit ACK.

   (Transaction#ID; type-of-event; ACK)

2. When NEO module triggers TEEM to reconfigure all related traffic flow paths (see Section 6.2.3.2), TEEM tries to configure the new path. It the configuration successes, TEEM sends back to NEO an Acknowledgment message.

   (network-node#ID; type-of-operation; UE#ID1; veNB#ID; Anchor#ID; ACK)

   Contrarily, if the new path cannot be configured, TEEM sends back to NEO a Not Acknowledgment message.

   (network-node#ID; type-of-operation; UE#ID1; veNB#ID; Anchor#ID; NACK)

TEEM-RAC

1) When RAC tells TEEM to configure a new path due congestion (see Section 6.2.4.2), TEEM tries to reconfigure the path. At the end of the operation, TEEM acknowledges RAC about the result of the operation with an *N*-tuple message.

   ((network-node#ID1, ACK | NACK); …; (network-node#ID*N*, ACK | NACK))

TEEM-iveC

1. When TEEM computes the RANaaS deployment algorithm (location/dimension of RANaaS), TEEM send a request to iveC functional split modules for the functional split information, e.g., the lower bound of the backhaul data rate and latency limitation between RANaaS and iSC.

2. When iveC functional split module receives the request from TEEM, it sends the information of functional split information to TEEM.

6.2.6 Measurement Module (MM)

6.2.6.1 Function overview

This module is in charge of configuring the iOpenFlow controller to perform the required measurements. These measurements might be dynamically requested by both the WP4 modules as well as WP2/WP3, and therefore has intra- and inter-WP interfaces. Envisioned metrics to be reported by the MM comprise: locally experienced congestion, available neighbours, available data rates, and number of connected UEs. The MM will support several reporting modes, e.g., asynchronous, periodic or event based.

6.2.6.2 Interactions with other modules

The modules that interact with MM module are NMM and iOpenFlow Controller, as shown in Figure 6-7. Also iveC functions may interact with MM module.

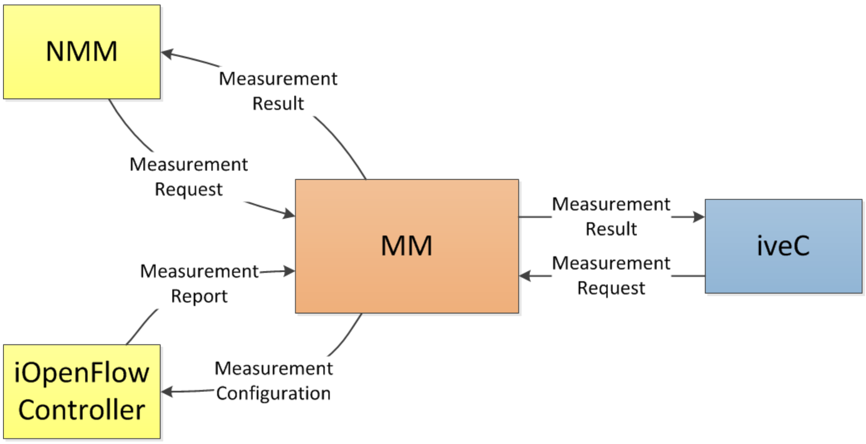


Figure 6-7 Interaction of MM module

MM–iOpenFlow Controller

1. When MM wants to configure a new measurement on a network node, it sends to iOpenFlow Controller a 5-tuple message. Such message contains the ADD command, the network node ID, the measurement rule, the type of measurement and the required granularity. The measurement type can be PERIODIC or ON-DEMAND. If measurement-type is PERIODIC, the measurement-granularity is the periodic interval (expressed in milliseconds) to which the measurement is performed. Instead, if measurement-type is ON-DEMAND, the measurement-granularity is left empty.

   (ADD; network-node#ID; measurement-rule; measurement-type; measurement-granularity)

   The measurement message is defined in Section 6.2.7.2.

2. When MM wants to remove measurement rule, it sends to iOpenFlow Controller a 5-tuple message. Such message contains the DEL command, the network node ID, the measurement rule, the type of measurement and the required granularity. The measurement type can be PERIODIC or ON-DEMAND. If measurement-type is PERIODIC, the measurement-granularity is the periodic interval (expressed in milliseconds) to which the measurement is performed. Instead, if measurement-type is ON-DEMAND, the measurement-granularity is left empty.

   (DEL; network-node#ID; measurement-rule; measurement-type; measurement-granularity)

MM–NMM

1. When NMM requires a measurement, it sends the request to MN in a 2-tuple message. Such message contains the network node ID, the measurement rule (e.g. periodic interval, per-flow counter etc.)

   (network-node#ID; measurement-rule)

2. Whenever MM collects a measurement requested by NMM, it sends the result to NMM in a 3-tuple message. Such message contains the network node ID, the measurement rule and the measurement's data.

   (network-node#ID; measurement-rule; measurement-result)

MM-iveC

1. When the iveC requires measurements (e.g., traffic information or modulation coding scheme between RANaaS and iSC/eNB), it sends the request to MN in a 2-tuple message. Such message contains the network node ID, the measurement rule (e.g. periodic interval, per-flow counter etc.)

(network-node#ID; measurement-rule)

2. Whenever MM collects a measurement requested by the iveC, it sends the result back in a 3-tuple message. Such message contains the network node ID, the measurement rule and the measurement's data.

(network-node#ID; measurement-rule; measurement-result)

6.2.7 iOpenFlow Controller

6.2.7.1 Function overview

This controller is a critical entity located at the iNC, extended from OpenFlow controller, taking care of all the protocol interactions with the rest of the WP4 network entities which only need to support OpenFlow, using the so-called Southbound API.

6.2.7.2 Interactions with other modules

The module of iOpenFlow Controller mainly interacts with two other modules, i.e., NMM and MM, as shown in Figure 6-8. iOpenFlow Controller is the module within iNC responsible of translating modules' requests into OpenFlow protocol.

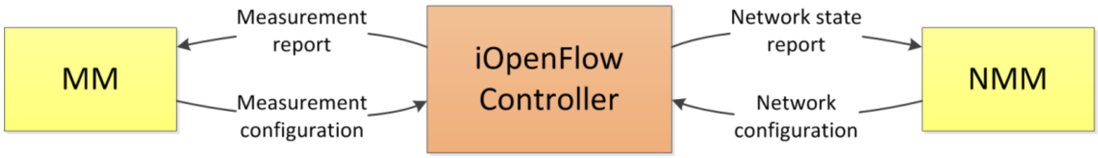


Figure 6-8 Interaction with iOpenFlow Controller

iOpenFlow Controller–MM

1. Whenever iOpenFlow Controller performs a measurement configured by MM, it sends the result to MM in a 3-tuple message. Such message contains the network node ID, the measurement rule and the measurement's data.

(network-node#ID, measurement-rule, measurement-result)

iOpenFlow Controller–NMM

1. When NMM requires the full view of the network, iOpenFlow Controller sends back to NMM the graph representing the network which uses adjacency lists for defining the link between the nodes. Each node contains all the related information, such as: ID, ports, characteristics of each port (fibre-optic, mm wave, etc.), and the IDs of all the neighbours. Therefore, the graph is sent in an *N*-tuple message, where N is the number of nodes in the network.

(node1, node2, …, nodeN)

2. When NMM asks iOpenFlow Controller to perform some operation on the network, such as configuring a forwarding rule, switch on/off a node, etc., iOpenFlow Controller tries to accomplish NMM's request performing the correspondent OpenFlow operations. After doing so, iOpenFlow Controller acknowledges NMM with a 2-tuple message.

(operation, ACK | NACK)

7 Cost analysis

WP4 enables the support of RAN Layer 1-3 CTs developed in WP2 and WP3. For that purpose, the performance of the potential transport technologies has been analysed in section 4, while section 5 details the proposed CTs for providing the network with the required functionalities. In order to carry out a more complete analysis, an additional topic that needs to be addressed is the cost of the network infrastructure (and particularly, the transport infrastructure) that should be deployed to support the iJOIN architecture. This section is intended to focus on this topic. It should be noticed that the cost of deploying a transport infrastructure for supporting the centralisation of the radio interface processing is the main practical obstacle for the use of the Cloud RAN architecture by operators and one of the main drivers for the adoption of the functional split concept.

In order to make the analysis more flexible, instead of focusing in the cost analysis of a representative scenario (which is the usual methodology), the section presents a generic, parameterised model that can be configured to represent different deployment scenarios. The focus of our research has been the estimation of deployment cost of networks including the transport infrastructure. This work also allows us to compute the cost of networks using technologies proposed by iJOIN and as a result, facilitates a comparison of the deployment costs of networks using iJOIN technologies and those that do not. To be more precise, we compare Cloud-RAN based networks versus traditional LTE networks. The framework used can be described in two parts. The first deals with the model which is used to obtain the framework to calculate the deployment cost and the second describes the dependence of deployment cost on information processing costs and details how these costs can be mapped to those required as inputs to the deployment cost calculation framework.

7.1 Cost Calculation Framework

7.1.1 System Model

The four network components we consider are users, base stations, backhaul nodes, and data centers. This network model can be visualized as shown in Figure 7-1.

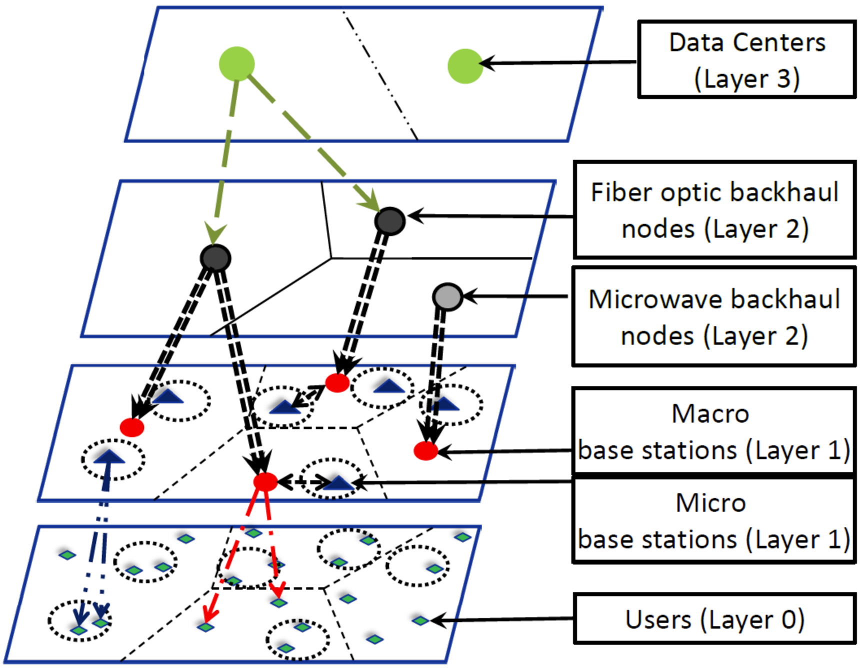


Figure 7-1: An illustration of a 4 layer network model

The lowest layer (layer 0) consists of users represented by a homogeneous Poisson process $\Phi_0 \subset R^2$ with intensity $\lambda_0 > 0$. Similarly, the topmost layer (layer 3) consists of data centres modelled by a homogeneous Poisson process $\Phi_3 \subset R^2$ with intensity $\lambda_3 > 0$. Layer 2 consists of both fibre optic and microwave backhaul nodes which are modelled using a stationary mixed Poisson process $\Phi_2 \subset R^2$ with intensity $\lambda_2 = p\lambda_{2MW} + (1-p)\lambda_{2OF}$, in which $\lambda_{2MW} > 0$ is the intensity of the microwave backhaul and $\lambda_{2OF} > 0$ is the intensity of the fibre optic backhaul. The penultimate layer (layer 1) consists of base stations (macro and micro base stations) represented by a stationary Poisson cluster process $\Phi_1 \subset \mathrm{R}^2$ consisting of two parts: cluster centres representing macro base stations and cluster members representing micro base stations. The intensity of the stationary Poisson cluster process is $\lambda_1 = \lambda_{1c}(1 + \lambda_{1m})$. Furthermore, we assume that only connections between adjacent layers are allowed, e.g., backhaul nodes cannot communicate with the users directly. Our work also does not explicitly consider costs incurred while connecting backhaul nodes to each other via a mesh network, etc. as well as the rate improvements in data centres due to the use of Coordinate Multi-Point (CoMP) techniques. Therefore, it can be assumed that the deployment costs computed using this framework are those that can be achieved even if very advanced techniques are not used. An important factor that determines the final deployment cost is the number of users that the network needs to cater to and the number of users that are connected to a given network component. This is also an aspect which has been included in our model. Next, we visit the framework which allows modelling data processing costs.

7.1.2 Data Processing Model

This subsection relates costs induced by operating the communication infrastructure to costs required for processing information in a Cloud-RAN system with a heterogeneous backhaul. The communication infrastructure spans multiple layers and is composed of the base station layer as well as the backhaul layer. Furthermore, the data centre layer also processes all incoming and outgoing transmissions. The processing requires ample computational resources which are dependent directly on the parameterization and operating regime of the mobile network. A major contributor to the cost of a Cloud-RAN system is the data centre layer. If a data centre is provided with too few computational resources, computational outage occurs. In which case, a transmission may not be successfully decoded though the channel quality is satisfactory. In contrast, if the system is over provisioned, it will be underutilized most of the time, which reduces the cost effectiveness of a centralized system. A majority of the uplink processing resources are required for the decoder, i.e., more than 80% of the overall processing resources. Additionally, while the processing demand in the downlink is fairly predictable, it is highly variable in the uplink. Therefore, this work considers solely the uplink decoder for dimensioning the data processing resources required. We use expressions for the complexity of the decoder as well as the outage probability and outage processing demand derived in [12] and (see also iJOIN deliverable D5.2, Chapter 5) to obtain cost values to be utilized in the deployment cost analysis.

7.1.3 Components of Deployment Costs

Typical deployment costs incurred by a service provider can broadly be classified into equipment cost, capacity cost, and infrastructure cost. The *equipment cost* C_i (in \$/device) represents the cost of a device deployed in a particular layer i. More specifically, the equipment cost of a typical backhaul node C_2 is a linear combination of $C_{2\mathrm{MW}}$ and $C_{2\mathrm{OF}}$ where $C_{2\mathrm{MW}}$ and $C_{2\mathrm{OF}}$ are the equipment costs of a microwave backhaul device and a fiber optic backhaul device, respectively. The *capacity cost* is the cost of connecting a device at point x in layer i to another device at point o in layer $i+1$ for a given capacity requirement. This cost is considered to be of the form $A_{i,i+1}\, g(\|x\|)$, where $A_{i,i+1} > 0$ is the base cost to achieve a certain capacity (or data rate) and $g(\|x\|)$ is a function of the distance $\|x\|$ which determines how the base cost scales with distance. For simplicity, $g(\|x\|) = \|x\|^{\beta_{i,i+1}}$ where $\beta_{i,i+1} \geq 0$. Similarly, *infrastructure cost* is defined as the expense incurred to ensure that a point x of layer i and the point o in layer $i+1$ are connected. It is considered to be of the form $B_{i,i+1} h(\|x\|)$, where $B_{i,i+1} > 0$ is the base cost for a particular type of installation) and $h(\|x\|)$ is a function of the distance $\|x\|$ between the two points under consideration. Once again, for ease of computation, $h(\|x\|)$ is taken to be $\|x\|^{\theta_{i,i+1}}$ where $\theta_{i,i+1} \geq 0$ determines how fast the base infrastructure cost increases with distance.

7.1.4 Method of Calculating Deployment Costs

Using the framework described above results in the following theorem.

Theorem: *In a 4-layer model that uses power law functions to describe capacity and infrastructure costs, the expected cost of deploying a data center is given by*

$$C_{\Phi_3} = \frac{\lambda_2}{\lambda_3}\left[C_2 + \frac{\lambda_0}{\lambda_2}\left(A'_{2,3}\frac{\Gamma\left(\frac{\beta_{2,3}}{2}+1\right)}{(\pi\lambda_3)^{\beta_{2,3}/2}} + A''_{2,3}\right) + B_{2,3}\frac{\Gamma\left(\frac{\theta_{2,3}}{2}+1\right)}{(\pi\lambda_3)^{\theta_{2,3}/2}} + \frac{\lambda_1}{\lambda_2}\left\{C_1 + \frac{\lambda_0}{\lambda_1}\Psi_1(P) + \Psi_2(P) + \frac{\lambda_0}{\lambda_1}(\Psi_3(P)+\Psi_4(P))\right\}\right]$$

Where the arguments for functions $\Psi_1, \Psi_2, \Psi_3,$ and Ψ_4 have been dropped for the sake of readability. The functions are defined by

$$\Psi_1(A_{1,2}, \beta_{1,2}, \lambda_{2MW}, \lambda_{2OF}, p) = A_{1,2}\left[\frac{p\Gamma\left(\frac{\beta_{1,2}}{2}+1\right)}{(\pi\lambda_{2MW})^{\beta_{1,2}/2}} + \frac{(1-p)\Gamma\left(\frac{\beta_{1,2}}{2}+1\right)}{(\pi\lambda_{2OF})^{\beta_{1,2}/2}}\right]$$

$$\Psi_2(B_{1,2}, \theta_{1,2}, \lambda_{2MW}, \lambda_{2OF}, p) = B_{1,2}\left[\frac{p\Gamma\left(\frac{\theta_{1,2}}{2}+1\right)}{(\pi\lambda_{2MW})^{\theta_{1,2}/2}} + \frac{(1-p)\Gamma\left(\frac{\theta_{1,2}}{2}+1\right)}{(\pi\lambda_{2OF})^{\theta_{1,2}/2}}\right]$$

$$\Psi_3(A_{0,1}, \beta_{0,1}, \lambda_{1c}, \lambda_{1m}, f(\cdot), \sigma^2) = A_{0,1}\lambda_1\int_{R^+} r^{\beta_{0,1}} P_1^o(b(o,r))dr$$

$$\Psi_4(B_{0,1}, \theta_{0,1}, \lambda_{1c}, \lambda_{1m}, f(\cdot), \sigma^2) = B_{0,1}\lambda_1\int_{R^+} r^{\theta_{0,1}} P_1^o(b(o,r))dr$$

Wherein $\mathbb{P}_1^o(\cdot)$ is the Palm distribution with respect to Φ_1.

A detailed proof of the above theorem has been provided in [13]. Then, using the finding above, the total cost of such a network is given by $C_{\mathrm{TOT}} = \lambda_3(C_3 + C_{\Phi_3})$.

Note that though expressions for $\Psi_3(\cdot)$ and $\Psi_4(\cdot)$ are not closed form expressions like those obtained for the other terms, solving them numerically is quite simple and takes only a few seconds on commercially available software.

7.2 Preliminary Results and Future Evaluation

The above framework has been used to obtain preliminary results for the cost-efficiency of the proposed iJOIN system. In particular, we compare results for a (conventional) distributed LTE implementation (DRAN) and three different configurations of iJOIN, i.e., with a maximum of 8 iterations, and with a link-adaptation offset of 0.4dB and 0.9dB. The corresponding results are shown in Figure 7-2. We can see that for a very low density of data centers, the cost for iJOIN exceeds the cost for DRAN. The main cost-driver is backhaul costs because a very high-capacity backhaul would be required. For increasing density of data centres, the deployment cost drops until it reaches an optimum where backhaul cost is low and a reasonable amount of data centres are deployed. If the density is further increased, the overall cost increases again due to fixed infrastructure cost per data centre.

We can further observe that the three iJOIN implementation options are comparably cost-efficient. The reason is the trade-off of cost for processing hardware and radio access points. While a higher link-adaptation offset reduces the computational complexity and therefore the cost for processing hardware, it requires additional radio access points. However, this also implies that the processing delay at the central entity can be scaled while being cost-neutral as the system may be operated at higher link-adaptation offset while maintaining the required system capacity.

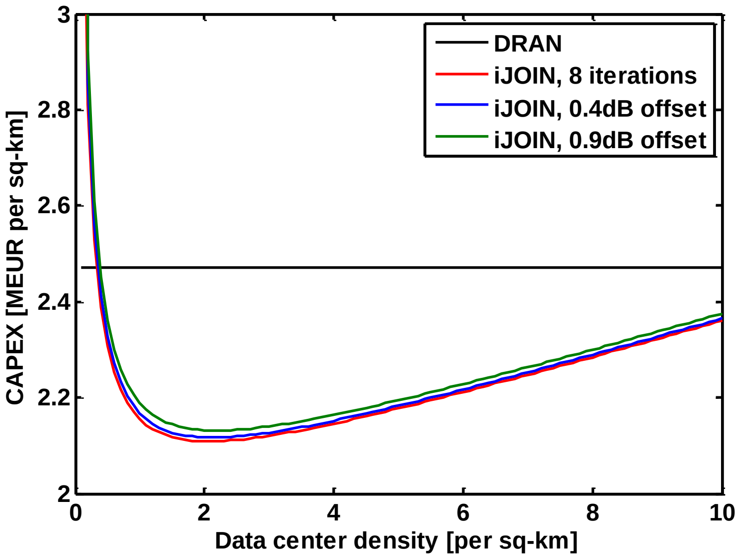


Figure 7-2 Preliminary results

8 Evaluation Methodology and Objectives

In this section, the evaluation methodology for each of the different CTs is described. The results of the evaluation process will be reported in the next WP4 deliverable D4.3. Furthermore, this section discusses the integration of the different CTs proposed in the WP in order to achieve the desired objectives defined by the project.

8.1 Evaluation methodology

In this section, the project evaluation framework is briefly introduced in order to assess which CTs are relevant for the proposed scenarios and metrics. Furthermore, the expected impact of WP4 CTs is explored.

8.1.1 Evaluation framework

WP4 evaluation methodology of the different CTs is consistent with the general framework adopted by iJOIN for the evaluation of the CTs in other WPs. This framework is based on the use of a set of four common scenarios proposed by WP5 and four key metrics to be used in order to assess the CTs performance. WP4 is in charge of network management and to make operative the network for WP2 and WP3 CTs. Therefore, WP4 CTs are fully applicable to all common scenarios as shown in the following table:

Table 8-1 Common scenarios

Scenario	CT4.1	CT4.2	CT4.3	CT4.4	CT4.5
1. Stadium	Y	Y	Y	Y	Y
2. Square	Y	Y	Y	Y	Y
3. Wide-area continuous coverage	Y	Y	Y	Y	Y
4. Indoor (Airport / Shopping Mall)	Y	Y	Y	Y	Y

Y = the CT can be applied to the CS; **Y** = the CT can be applied to the CT and it will be evaluated in the CS;

WP4 CTs are going to be evaluated mainly in common scenario 2 and 3 since they represent the most challenging network topology according to WP4's perspective. In particular, the evaluation should use the parameters that have been defined in the context of WP5 for the different scenarios [25]. Not all iJOIN metrics are equally treated by all WP4 CTs, i.e., CTs have different main objectives. The mapping between WP4 CTs and metrics is indicated in Table 8-2. The meaning of the symbols is the following: the "++" symbol indicates that a given CT positively affects a specific objective; the "+" symbol means that a CT has a collateral positive impact on a given objective; finally, the "0" represents a negligible impact. Furthermore, we recall here that iJOIN targets improvements in terms of Area Throughput, Energy Efficiency, Cost Efficiency, and Utilisation Efficiency. As it can be observed in Table 8-2, WP4 CTs mostly address Utilisation Efficiency, while no CT explicitly addresses the Area Throughput metric. This is mainly due to the fact that WP4 CTs support Layer 1-3 technologies in WP2 and WP3 which primarily improve Area Throughput. Indeed, one of the main roles of WP4 is to make sure that Area Throughput CTs can operate as intended by providing the required connectivity.

Table 8-2 Qualitative impact of the WP4 CTs with respect to the global iJOIN objectives.

	Energy Eff.	Area Tput.	Utilisation Eff.	Cost Eff.
CT4.1	0	0	++	0
CT4.2	++	0	0	0
CT4.3	0	0	++	++
CT4.4	0	0	++	+
CT4.5	0	0	++	0

0 = the metric is not affected by the CT; **+** = the CT has a collateral positive impact on the metric; **++** = the CT has a positive impact on the metric

A second feature of the evaluation framework that should be considered is whether the CT will be evaluated by means of simulations or using one of the project test-beds. In this sense, it should be noted that for some of the CTs the main aspect to be considered is not the performance but the support of a given functionality which may be better evaluated in a test-bed.

8.1.2 Evaluation methodology for the CTs

CT 4.1: Distributed IP Anchoring and Mobility Management

In our approach, we try to reduce the load in the backhaul network by smartly assigning anchors to the UEs and by offloading some type of traffic. In this way, CT4.1 can increase the utilisation efficiency in the backhaul network above the RANaaS. A second important aspect regarding the Mobility Management is the quickness at which the handover operations are performed. Indeed, in iJOIN the mobility is provided through an SDN approach instead of using the classical mobility protocols. The performance of this new approach will be assessed in order to ensure that the mobility is provided in a timely manner. This is done by managing, controlling and evaluating the whole mobility process. Wide-area continuous coverage is the common scenario considered for evaluating this CT. Moreover, the CT will be implemented and evaluated on SDN Test-bed.

Regarding the backhaul offloading we will compare the network load when CT4.1 is employed and when is not (a central anchor is used for every UE). We will evaluate the following cases:

- There is an iLGW in the network; UEs' traffic is partially offloaded through it.
- Different anchors are selected for different UEs; this allows spreading the UEs' traffic in the network.

The evaluation of CT4.1 considers also the time required for performing a handover. The overall mobility procedure, which can be triggered by several factors, will be analysed and evaluate. The considered cases are:

- Initial UE attachment: when a UE connects to the RANaaS for the first time.
- Intra-anchor UE mobility: when a UE moves in the RANaaS and the AMM decides to not change the anchor.
- Inter-anchor UE mobility: when a UE moves in the RANaaS changing its point of attachment.
- New anchor assignment: when the AMM decides to assign a new anchor. This may happen even if the UE does not move. The anchor selection may be performed at flow level.
- Energy triggered mobility: when the mobility is triggered by energy purpose.
- Congestion triggered mobility: when the mobility is triggered by a network's congestion.

We obtained some preliminary results regarding the intra-anchor UE mobility. AMM has been implemented on SDN Test-bed and we measured experimentally the Layer 2 and 3 handover latencies and ping disconnectivity, understanding ping disconnectivity as the time when no ping echo request were answered. Figure 8-1 reports the cumulative distribution function (CDF) of handover latency where 190 handovers for a UE with 2 assigned anchors were performed. Some absolute values for 95% percentile are:

- 95% percentile total layer 2 handover time: 18ms
- 95% percentile total layer 2+3 handover time: 44ms
- 95% percentile for ping disconnectivity: 51ms

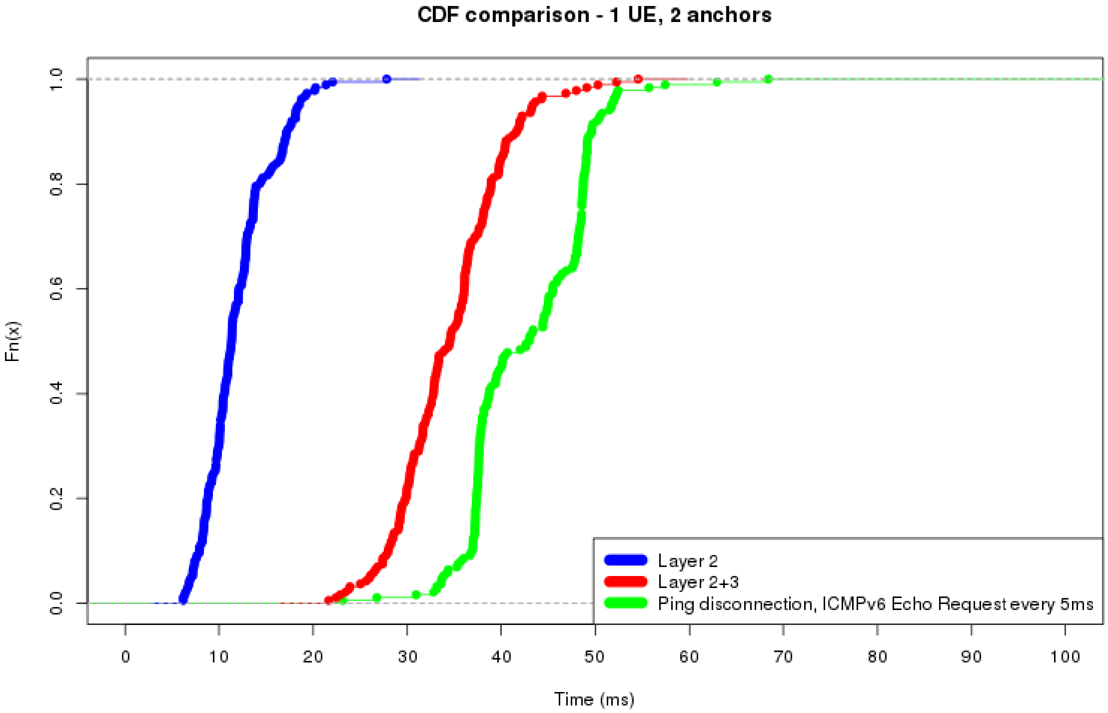


Figure 8-1 CDF for Layer 2, Layer 3 Handovers and Ping Disconnectivity

The results show that SDN can be used for providing mobility in a timely manner. More extensive results will be included in the future derivable.

CT 4.2: Network Wide Energy Optimisation

Considering a cellular simulator planned in MATLAB, we have evaluated the energy savings for different scenarios of different cellular networks. Yet, we have already given some initial insight and numerical results about the achievable energy savings, by taking into account sleeping modes of the iSCs.

Thus, in the following, we briefly present some numerical results and discuss some initial insights these offer [45]. We consider a topology composed of 120 iSC, and 2 macro-cells in an area of 45km^2, while evaluating our proposed algorithms for CT4.2. In Figure 8-3 the top curve corresponds to the portion of energy saved when we consider only the first constraint active, if the switching-off duration is supposed to last 10min. On the x-axis we increase the constraint threshold and plot the respective energy savings. As can be seen there, increasing the threshold (i.e., making the constraint less strict) increases savings, as it allows for more iSCs to be switched off.

For example, we can save up to 68% of the total energy consumption of our cellular network, for $P_{failure}$ = 0.4. The bottom curve also shows the energy savings, but now with the other two constraints active as well: the blocking threshold is fixed at 10^{-3} and the delay threshold at D_{max}=50msec. As can be seen there, savings increase again, but less sharply, as the other two constraints can become the “bottleneck” for a switch-off decision, especially as $P_{failure}$ increases. For example, now, with $P_{failure}$=0.4 and the other two thresholds fixed, the portion of energy saving can be up to 30%. Similarly, Figure 8-2 and 8-3 depict the portion of the energy saved, by considering the other two constraints. For example, the top (bottom) curve of Figure 8-2 shows that the portion of energy savings can be up to 50% (28%), by considering only the blocking probability constraint (plus the other two with fixed thresholds at $P_{failure}$ = 0.4 and D_{max}=50msec). Finally, the portion of energy savings for the delay constraint can be 70% by maintaining it to 100msec, and 30% by holding the other two fixed at P_{block} = 10^{-3} and D_{max}=50msec.

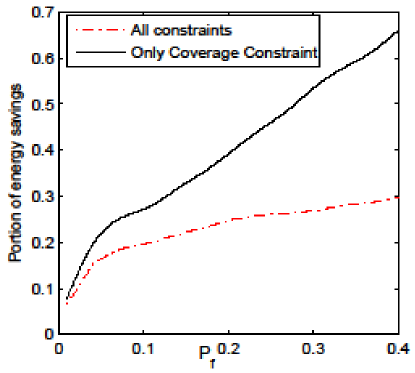


Figure 8-2 Failure Prob. VS Energy Saving

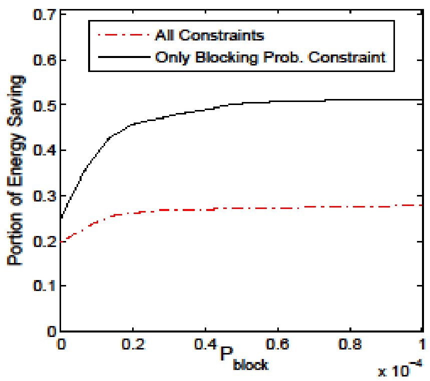


Figure 8-3 Blocking Prob. VS Energy Saving

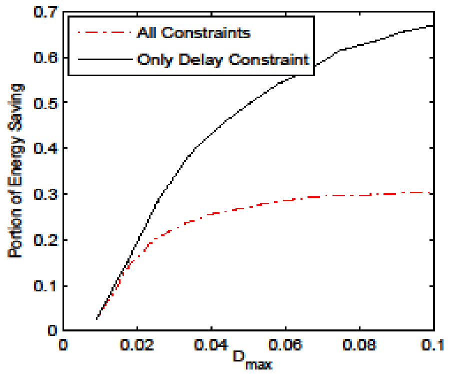


Figure 8-4 Service Delay VS Energy Saving

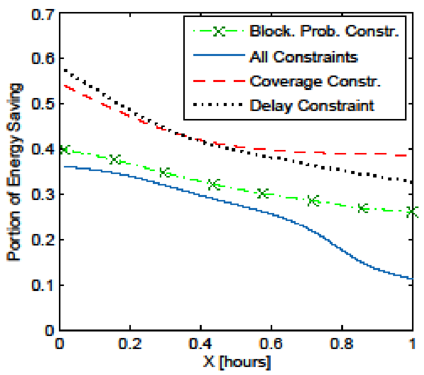


Figure 8-5 Switching-off Period VS Energy Saving

Another interesting parameter is X, the duration of the switching-off period. Figure 8-5 depicts the portion of energy saved for different values of X. As can be seen there, the maximum energy savings is achievable when X is relatively small, but start decreasing and eventually flatten out, as X increases. The reason is that, for small X, one needs to only consider the impact of active users when evaluating the constraint and the impact of hand overs to neighbouring iSCs. However, as X increases, there is a higher chance connected and disconnected users will add to the total transferred load and thus a bigger impact on existing and remote users, which might prevent us from switching off an iSC. Finally, the plot for each respective constraint is not always linear, as some additional phenomena, such as convergence to stationarity for the stochastic systems we use in constraints 2 and 3, also affect systems' behaviour.

To demonstrate the benefit of the CoMP-enhanced scheme we have considered a virtual eNB (veNB) consisting a RANaaS platform and 19 iSCs. iTNs power consumption was omitted for now, however, we still considered the consumption from microwave backhaul links and switches at iSCs. For each element's power consumption, depending on the cells' load, we have adopted the examples of measures provided in D5.2. Furthermore, considering only the coverage constraint we used (for consistency with the conventional scheme) the expected SNR to calculate outage probability of a UE that can potentially be handed off to cluster set q={1,…Q_c} comprising a total number $M_{q,c}$ of iSCs. Thus, the expected SNR of lth UE served by this cluster was given by:

$$SNR_{l,q,c} = \frac{\sum_{j=1}^{M_{q,c}} G_{lj} p_j}{N_0} \qquad \text{(a)}$$

Where G_{lj}, p_j and N_0 denote the iSC-UE path loss, the per-iSC transmission power and the noise power, respectively. Based on the aforementioned setup we performed Monte-Carlo simulations and compared the system energy savings between the conventional and a CoMP-enhanced switch on/off scheme, In particular, we considered a heuristic adaptive clustering scheme according to which 1) a maximum of 2 cells can form a CoMP cluster and 2) when underutilized cells cannot switch off using the conventional scheme (i.e. cannot handover all their UEs to neighbouring cells), the best feasible clustering option that can realize this switch off is adopted.

Figure 8-1 illustrates the comparison result for various values of switch-off duration. We can observe that even with the considered heuristic 2-cell clustering method, up to around 3-fold improvement in system energy savings can be achieved when iSCs are allowed to adapt to traffic conditions more often (i.e. low switch-off duration). The large gains are obtained due to the fact that generally more (if not all) underutilized cells are able to switch-off and drive the backhaul links into idle state, At the same time, the consumption at the high processing capability RANaaS platform is kept at reasonable levels despite the additional CoMP needs. For high switch-off duration, the savings (as expected) and also the benefit over the conventional scheme decreases due to the fact that iSCs will have higher load in general, thus, they will able to receive users from underutilized cells less often.

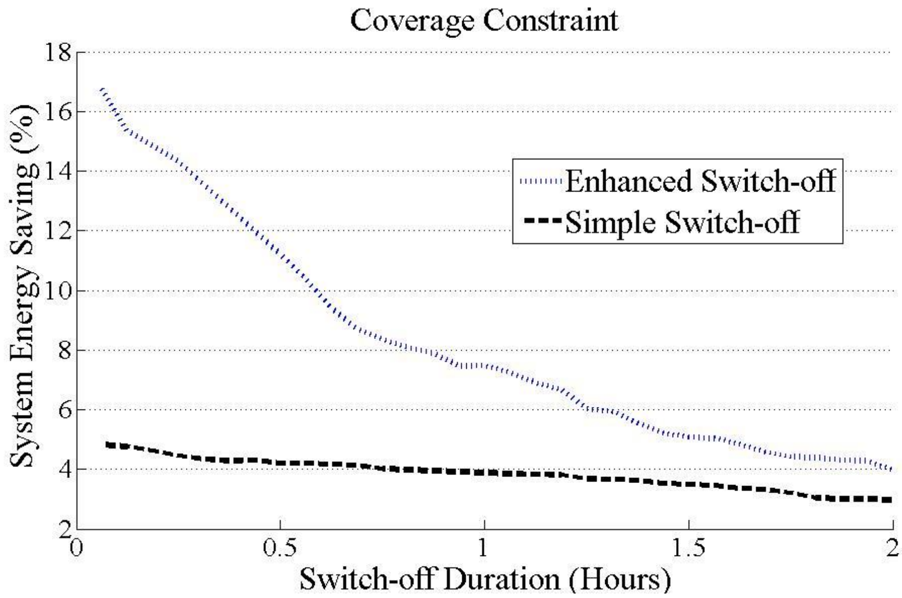


Figure 8-1 Switching-off Period VS Energy Saving

Finally, another interesting issue that will be investigated at a next step is the sleeping modes of iTN nodes, and how we can combine *jointly* the iSCs and iTNs, in order to achieve the best energy savings.

CT 4.3: Joint Path Management and Topology Control

In CT4.3, we work on the topic of planning RANaaS in dense small cell deployments. Conceptual evaluation is presented in the Section 5.3, where the impacts on latency, computation resource as well as routing are analysed when placing RANaaS platforms in different locations, namely P/S –GW, iTN and eNB.

Further evaluation of the CT is going to be carried out by means of simulations. The genetic algorithm of RANaaS deployment problem is implemented for simulations. The main goal of optimally positioning/dimensioning RANaaS platform is to improve the efficiency of path computation (Utilisation Efficiency) and to save the cost of RANaaS deployment (Cost Efficiency). Therefore, the evaluation includes the following two parts:

1) Utilisation Efficiency

- **Benchmark:** As described in the conceptual evaluation in Section 5.2.1, the location of RANaaS may have a great impact on the efficiency of path computation in TEEM. Therefore, the end-to-end paths (iSC to Gateway) are considered in our algorithm in order that the path could be routed efficiently among small cells, RANaaS platforms and gateways. For the sake of evaluation, we devise another algorithm without considering the path effect as a benchmark.
- **Performance metric:** The paths are computed based on the RANaaS deployment calculated by our algorithm and benchmark algorithm, respectively. Based on the path computation, the network utilisation (residual backhaul capacity) is calculated as performance metric.

2) Cost Efficiency

- **Benchmark:** The algorithm locates and dimensions the RANaaS platforms according to the topology, traffic requirement and requirement of functional split. A deployment of RANaaS platforms without considering these effects is used as the benchmark, where RANaaS platforms are co-located with eNB (edge of the backhaul network) and associates with the iSCs nearby.
- **Performance metric**: the performance metric is the sum of the cost, including the cost of processing resource and infrastructure cost.

CT 4.4: Routing and Congestion Control Mechanisms

As the testing of the congestion control procedures proposed would require the access to low level control functions in switches, it is not considered feasible to test them in the proposed test-bed.

For this reason, the evaluation of the CT will be carried out by means of simulations. The model to be used will be a simple one, based on the consideration of a single node with variable number of ingress and egress ports with variable capacity. For this purposes, an ad-hoc simulator implemented in Matlab has been developed.

The evaluation would require the simulation of different information flows associated to different functional splits as well as conventional information flows associated a conventional LTE calls. The bit rates associated to the functional split flows will be based on the estimations carried out in other iJOIN WPs. An example of these estimations is represented in the following figure:

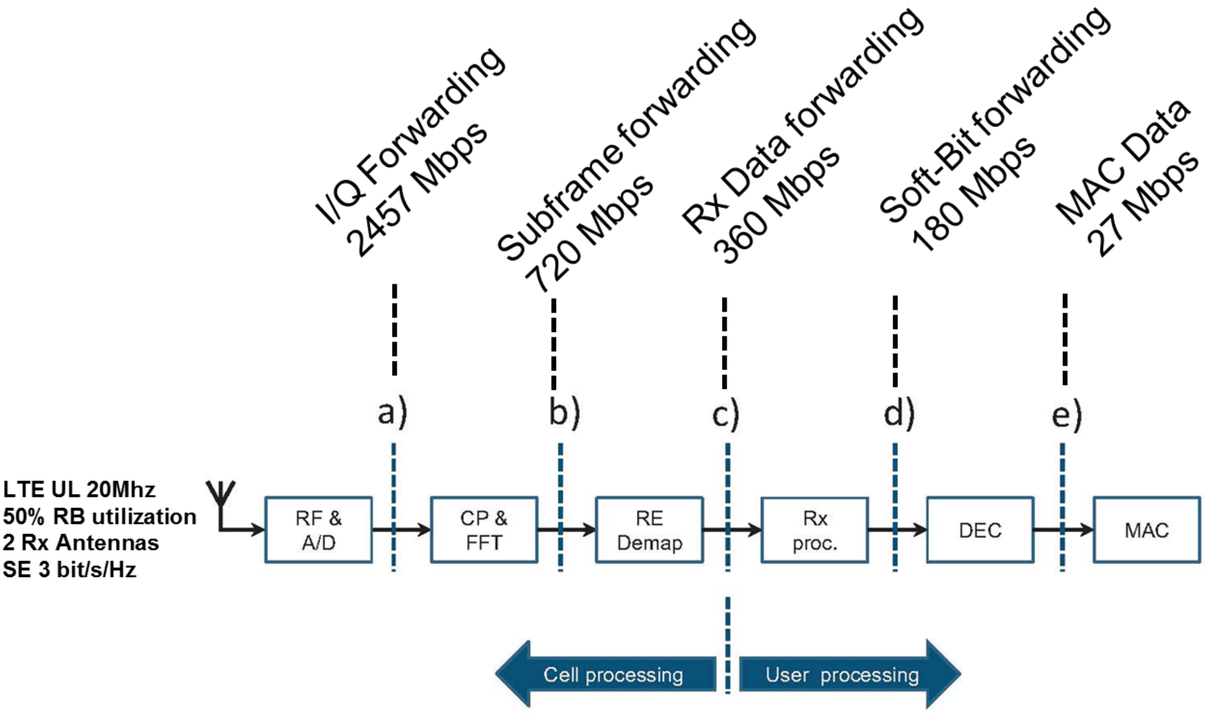


Figure 8-6 LTE bandwidth demands as a function of the functional split (UL)

For the conventional flows the characterization will be based on values available in the technical literature. Uplink and downlink directions will be simulated separately. The simulator will implement the virtual queue mechanisms proposed by the CT, as well as the effect of the congestion control procedures implemented in other nodes outside the iTN in the simulation process, different control strategies (basically, defining threshold values of the virtual queues and values for the other CT control parameters) will be implemented, based on the measured values in the different elements of the mechanism.

The main objectives of the evaluation to be evaluated are:

- Estimation of the switching capacity required in the iTN nodes for the different common scenarios defined by iJOIN WP5.

- Effective capacity used in iTNs associated with different traffic profiles and functional splits. Virtual queues mechanisms are known for exchanging a lower capacity for a lower latency.
- Effectiveness of Explicit Congestion Notifications and packet drop mechanisms in non-constant bit rate flows for congestion mitigation.
- Evaluation of the feasibility of implementing the congestion control procedures in a centralized way (i.e., in the iNC).

CT 4.5: Network Wide Scheduling and Load Balancing

Centralised and decentralised mechanisms have to be considered, in a SDN environment, in which the network control plane is decoupled from the physical topology. Some traffic management related decisions, e.g., load balancing algorithms, will require a global, centralised view of the topology and medium/longer term traffic statistics, while others will require a local and timely view (e.g., virtual queue occupancies) in order to optimally react to the ongoing traffic mix.

The evaluation of the CT will be carried out by means of simulations. The model to be used will be a cellular network scenario implemented in Matlab. Our aim is to test how our algorithm reacts in different use cases and parameters, e.g. in scenarios with high variability between the traffic loads.

The evaluation would require the simulation of different information flows, e.g. dedicated and best-effort. The main objectives of the evaluation are:

- Given our desired policy, to find the optimal user-association behaviour.
- Different scenarios, with traffic-variability, and heterogeneous networks.
- How can we commit load-variations, in short time-scales?
- Scheduling policies, based on local information.

8.2 Integration of technologies towards iJOIN objectives

Integration is a key objective for the iJOIN functional architecture in order to achieve energy-efficiency, cost-efficiency, utilisation-efficiency and area-throughput. The functional architecture requires by design a clear cooperation between WP4 modules and also between WP4 and other WPs, i.e. WP2 and WP3.

8.2.1 CT's compatibility

In this Section, we aim to obtain a preliminary comparison of the overall WP4 CTs as well to define possible configurations of compatible CTs, which can be integrated in order to achieve the global iJOIN targets. Table 8-3 reports the compatibility of the WP4 CTs, the "Y" symbol indicates that two CTs are compatible, the "C" symbol means that a conflict can eventually arise if the interaction between the two CTs is not managed properly. For each possible conflicting interaction, a dedicated paragraph is dedicated in the following.

Table 8-3 Compatibility of the WP4 CTs

	CT4.1	**CT4.2**	**CT4.3**	**CT4.4**	**CT4.5**
CT4.1		C	Y	Y	Y
CT4.2			Y	Y	C
CT4.3				Y	Y
CT4.4					Y
CT4.5					

Y = Compatible; **C** = Conflict;

CT4.1 and CT4.2 incompatibility

A conflict can eventually appear when CT4.2 decides to switch off a branch of the network and does not consider the decision taken by CT4.1. To each UE, a set of anchors is assigned depending on the required services. An anchor can support a set of services while another anchor does not support them. If CT4.2

decides to switch off an anchor and there is no other anchor able to provide the same services, CT4.2 cannot switch off that node. Therefore, the possible conflict is solved by taking into account this aspect during the design of the interaction between the two CTs. The interaction described in Section 6.2.1.2 considers this conflict.

CT4.2 and CT4.5 compatibility

On the one hand, when an iJOIN element (e.g., iSC or iTN) is "under-utilised", the NEO component, tries to push more flow/users to neighbour nodes in order to switch off the low-utilised node. On the other hand, when an iJOIN element is "highly–utilised", *Load balancing* should try (depending on the desired policy) to assign or reroute flows to alternative nodes that are underutilised, in order to balance the load and improve user QoE. Thus, we can see that there is a direct interaction between these two CTs. The former attempts to reduce the usage of network resources to improve the energy performance from the perspective of the infrastructure provider, while the latter attempts to increase the usage of some network resources in order to improve the performance of users. Evidently, these two goals can be conflicting, and interaction between the two is needed. To this end, we propose a time-scale differentiation, as adopted in [14]; NEO algorithm will run in a "larger" time-scale and LB in a "finer" time-scale. This time-separation will offer not only confliction-avoidances, but also analytical tractability.

8.2.2 Integration of CTs results

In the following paragraph we report a preliminary result of CTs integration. The goal is to check whether is possible to sum together the results obtained for two different CTs. At this purpose, we report separately the results regarding Area Throughput, Energy Efficiency, Cost Efficiency, and Utilisation Efficiency targets. For each metric we report a comparison table and a description of the planned integration. In Table 8-4, Table 8-5, Table 8-6, and Table 8-7, the symbol "FC" means that obtained results can be summed together, while the symbol "TS" means that the results can be summed together if the CTs work at different timescales.

<u>Energy Efficiency</u>

Table 8-4 Energy Efficiency comparison

	CT4.1	CT4.2	CT4.3	CT4.4	CT4.5
CT4.1		Nan.	Nan.	Nan.	Nan.
CT4.2			Nan.	Nan.	TS
CT4.3				Nan.	Nan.
CT4.4					Nan.
CT4.5					

TS = CTs are compatible at different timescales; **Nan.** = not applicable, the two CTs does not address simultaneously the same metric;

CT4.2 and CT4.5 integration

As we already mentioned, we should make an assumption on time-scale separation that flow arrival and departure process follow: we assume that the corresponding user-association process (the time-scale of CT4.5) is much faster than that of the period on which the set of active BSs are determined (the time-scale of NEO).

Although the traffic pattern varies over time (as well as space) we could assume to be constant for a certain period of time (e.g. 1 hour). Since the time-scale for determining the set of active BSs is similar to the order of traffic-pattern changing, it is definitely much larger than that of flow arrival and departure, e.g. typically less than some minutes.

Area Throughput

Table 8-5 Area Throughput comparison

	CT4.1	CT4.2	CT4.3	CT4.4	CT4.5
CT4.1		Nan.	Nan.	Nan.	Nan.
CT4.2			Nan.	Nan.	Nan.
CT4.3				Nan.	Nan.
CT4.4					Nan.
CT4.5					

Nan. = not applicable, the two CTs does not address simultaneously the same metric;

Within WP4, none of the described CTs has an impact on area throughput metric.

Utilisation Efficiency

Table 8-6 Utilisation Efficiency comparison

	CT4.1	CT4.2	CT4.3	CT4.4	CT4.5
CT4.1		Nan.	FC	FC	Nan.
CT4.2			Nan.	Nan.	Nan.
CT4.3				FC	FC
CT4.4					TS
CT4.5					

FC = CTs are fully compatible; **TS** = CTs are compatible at different timescales; **Nan. =** not applicable, the two CTs does not address simultaneously the same metric;

CT4.1 and CT4.3 integration

CT4.1 aims to improve the utilisation efficiency by spreading the UEs over multiple and different anchors. CT4.3 improves the utilisation efficiency in the network's deployment phase. When the network is being deployed, CT4.3 finds the optimal RANaaS placement for improving this metric. Hence, the two CTs are fully compatible and the gains obtained by each CT can be summed together.

CT4.1 and CT4.4 integration

As the actions undertaken by CT4.4 do not consider the impact on the QoS/QoE of the users (they only take into account the welfare of the transport nodes), CT4.1 actions should have precedence over them. The interaction described in Section 6.2.1.2 considers this precedence.

CT4.3 and CT4.4 integration

CT4.3 (RANaaS placement) runs offline and it is used for optimising the deployment of the network. CT4.3 (Routing) runs online and routing decision are based on the status of the network. The congestion's information is provided by CT4.4 to CT4.3. The results can be summed together.

CT4.3 and CT4.5 integration

CT4.3 (RANaaS placement) runs offline and it is used for optimising the deployment of the network. CT4.3 (Routing) runs online and routing decision are based on the status of the network. The decision regarding the load balancing of the network is provided by C4.5 to CT4.3. The results can be summed together.

CT4.4 and CT4.5 integration

As the actions undertaken by CT4.4 do not consider the impact on the QoS/QoE of the users (they only take into account the welfare of the transport nodes), CT4.5 actions should have precedence over them. The reason for this prioritisation is easily understood with an example. If in a cell there is a significant number of users operating in bad propagation conditions (e.g., in indoors), there may be an overload at radio interface level, but no significant impact on the congestion of the iTNs will be experienced. In other words, load balancing and scheduling decisions are undertaken firstly, and then congestion control is used to alleviate potential congestion issues at the transport layer. If congestion finally happens, then it will correspond to CT4.5 to look for the adequate solutions to solve it. Nevertheless, CT 4.4 may activate some actions for reducing the bit rate of flows without changing the point of attachment (e.g., by packet dropping).

Cost Efficiency

Table 8-7 Cost Efficiency comparison

	CT4.1	**CT4.2**	**CT4.3**	**CT4.4**	**CT4.5**
CT4.1		Nan.	Nan.	Nan.	Nan.
CT4.2			Nan.	Nan.	Nan.
CT4.3				FC	Nan.
CT4.4					Nan.
CT4.5					

FC = CTs are fully compatible; **Nan. =** not applicable, the two CTs does not address simultaneously the same metric;

CT4.3 and CT4.4 integration

CT4.3 (RANaaS placement) runs offline and it is used for optimising the deployment of the network, CT4.4 runs online performing a congestion control in the network. CT4.4 support may allow for a greater flexibility to CT4.3 decisions, in terms of allowing the use of same transport technology for supporting different functional splits. In this sense, both CTs may cooperate towards lower network CAPEX.

9 Summary and Conclusions

This deliverable completes the specification of the WP4 architecture, by providing the full description of the set of candidate technologies applicable at the network layer for a dense deployment of small cells and a joint optimisation of access and backhaul networks, and by specifying the functional architecture, which links consistently the operation and improvement of all the CTs into a single system. In order to plan and prepare for the final testing phase, the objectives and methodology of the evaluation have been prepared.

In addition, two key contributions of this report are the initial analysis of the location of the RANaaS within the network, and the analysis of the implications of adopting an SDN-based architecture.

One of the main responsibilities of WP4 is computing, setting up and maintaining the paths within the backhaul network, in order to cope with the requirements imposed by the user applications and the functional split. An analysis of the characteristics (mainly delay and bandwidth) of several backhaul technologies is provided in this deliverable. This is very valuable information to evaluate if a given functional split functionality (designed within WP2 or WP3) is feasible or not.

In this deliverable, a detailed specification of the intra-WP4 modules interaction has been provided, building on top of what was identified in D4.1, and providing additional information on the parameters exchanged between the different modules. The purpose of this work has been to ensure that WP4 CTs are compatible and can collaboratively act together towards the achievement of common goals. A compatibility analysis of the different CTs has also been performed.

One critical aspect of the iJOIN architecture is the assessment of the cost of the transport infrastructure. This has been performed producing a generic, parameterised model that can be configured to represent different deployment scenarios.

Last but not least, we have presented our evaluation framework, which will be the basis for the evaluation work to be done in the last 6 months of the project.

From a dissemination point of view, several top level publications including WP4 work have been accepted. It is worth highlighting that one of them was selected as free COMSOC paper of the month. Our active participation and contribution to standardisation activities have also continued, resulting in several IETF WG adopted documents. Our Open Source contributions have been publicly released, and a demo took place in EuCNC 2014 showing early results from WP4 mobility CTs.

Acknowledgements and Disclaimer

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