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Abstract

We study intra-operator and inter-operator infrastructure sharing solutions from a TCO perspective, focusing on the benefits and trade-offs of distributed and centralised RAN architectures. Based on a detailed cost analysis, with costs extrapolated from real-world network deployments, we show that the benefits of network architectures based on intra-operator sharing via RAN-centralisation depend on deployment conditions that are a function of specific markets, like availability of fibre, site rental costs and site construction costs. For the case of inter-operator sharing the focus is on site sharing and fibre sharing. Our results showed that infrastructure sharing leads to significant reductions in TCO, in particular in markets where fibre deployment and site-rent represents a big portion of the costs. Finally, we briefly study the main implications of regulations on future deployments of centralised RAN architectures. In particular we focus on the case of inter-operator sharing, as specific regulations on site sharing and fronthaul sharing can have a big impact on the choice of deploying a centralised RAN.

Keywords

Infrastructure sharing, TCO, centralised/distributed RAN architecture, regulation.

Contents

Abbreviations

BBU	Base Band Units
BS	Base Station
CAPEX	Capital Expenditures
CoMP	Cooperative Multi-Point
CPRI	Common Public Radio Interface
CU	Central Unit
FTTH	Fibre to the Home
HTN	Heterogeneous Networks
LTE	Long Term Evolution
MIMO	Multi-Input Multi-Output
MVNO	Mobile Virtual Network Operators
OPEX	Operational Expenditure
P2P	Point-to-Point
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
SFP	Small form-Factor Pluggable
TCO	Total Cost of Ownership
TP	Transmission Points
WDM	Wavelength-Division Multiplexing

1 Executive summary[1]

In this document we study the business impact of intra-operator and inter-operator RAN sharing solutions based on hardware centralisation. The core of our study is a detailed Total Cost of Ownership (TCO) analysis, carried out considering state-of-art technical solutions and deployment assumptions obtained from real-world wireless networks.

For the case of intra-operator sharing, we consider three different deployment solutions: a distributed RAN deployment with microwave backhaul, a centralised RAN deployment with fibre-based fronthaul and a distributed RAN deployment with fibre-based backhaul.

For the case of inter-operator sharing we extend the intra-operator study by focusing on centralised RAN deployments and considering site sharing and fibre sharing. In particular, we study two cases of fibre sharing: one considering two operators deploying together the fibre fronthaul infrastructure and the other one considering one operator deploying the fibre infrastructure and another operator leasing the duct.

For the case of intra-operator sharing, we show that the benefits of network architectures based on full-centralisation depend on deployment assumptions that differ in specific markets, as for example availability of fibre, site rental cost and site construction costs. These results indicate the need of investigating hybrid centralised/distributed solutions that would allow the same performance benefit of fully centralised solutions, without incurring in the same costs.

For the case of inter-operator sharing, we show that sharing leads to significant reductions in TCO, in particular in markets where the cost of fibre deployment and the site-rent represent a big portion of the costs.

This document is organised as follows. In Section 2 we give an introduction about the different intra-operator and inter-operator infrastructure sharing solutions, ranging from the ones already deployed in real networks to the ones under consideration in the academic and industrial community. In Section 3, the core of this contribution, we give a quantitative TCO analysis. In Section 4 we give a summary about the impact of regulations on centralised deployments. Finally, in Section 5 we conclude the document.

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[1] We note that the TCO study has been carried out assuming realistic technical solutions and related cost estimations. Unfortunately, the details about the technical solutions and the costs of the different components cannot be disclosed because subject of company confidentiality. However, the results presented in Section 3 are obtained with the full set of assumptions, and therefore give a very realistic picture of the problem considered.

2 State of the art of network sharing solutions

In this section we give an overview of the state-of-art network sharing techniques. As spectrum sharing is out-of-the scope of this document, we refer to [M09] for an overview about spectrum sharing in the context of cellular systems.

2.1 Passive sharing

With passive sharing, one or more operators are sharing one or more of the following: site/location, mast, antennas and cooling units. The sites could be acquired or managed by a third individual. Costs for leasing the infrastructure could be equally shared by the different operators.

Passive sharing brings different gains. First, it allows reducing some of the biggest costs an operator has to support, i.e. site acquisition and maintenance that together account for a big portion of the TCO. Moreover, it can allow Quality of Service (QoS) differentiation between the operators sharing the same infrastructure, as these operators are using a different RAN (and a different core), that can be optimised in a different way. Then, it can be realised in a relatively simple way, as there are not main game stoppers from a technology point-of-view. It could allow a faster network update, and faster network extension due to the reduced costs, assuming an alignment between the deployment strategies of the operators sharing the infrastructure. It could also ease the entry of new mobile service providers, due to the reduced initial costs for infrastructure-deployment. Last but not least, passive sharing allows a reduced environmental impact due to the reduced infrastructure footprint required. Passive sharing is already widely implemented. For example, Vodafone and Telefónica have announced a deal to share mobile network infrastructure in Spain, UK, Germany and Ireland [VT09]. In India and China, passive sharing is mandated by the regulator [E09].

On the other side, passive sharing could not be a viable way of deploying networks in dense areas, where deployments based on small cells with hot-spot deployment are used as a QoS differentiator. Moreover, passive sharing could also lower the speed of infrastructure upgrade, in case of discrepancies between the network-rollout roadmaps of the different operators sharing the same mobile networks. With respect to RAN sharing, passive sharing requires a higher Capital Expenditures (CAPEX) and Operational Expenditure (OPEX), due to the fact that each service provider has to buy, operate and maintain a different base station unit.

2.2 Backhaul sharing

With backhaul sharing two or more individuals share the same backhaul infrastructure, for example the optical fibre connecting to the base stations. In the past backhaul sharing was seen as an important model for developing countries or for rural areas. Today the situation is changing, and backhaul sharing is becoming an important candidate also for well-developed parts of the world, as optical fibre is an important enabler for new network concepts and features such as heterogeneous networks (HTNs), Cooperative Multi-Point (CoMP) and centralised RAN.

In Section 4.2, we will discuss different approaches for backhaul (fronthaul) sharing and the role of regulator to foster the deployments of fibre based backhaul networks.

2.3 National roaming

National roaming refers to an agreement between two operators such that one of them is using some of the network components of the other to cover some geographical areas. National roaming can be used to facilitate the entrance of a new network operator. For example, in UK national roaming enabled the 3G network operator 3 to offer its customers the ability to make and receive calls in areas of the UK where 3 had not yet built its 3G network. Such calls were conveyed by O2's 2G network. In this specific case the agreement between 3 and O2 was achieved through commercial negotiation [O04]. In other cases, the regulator could force one or more incumbent operators to allow national roaming of a new entrant operator in their networks. Two or more operators could decide to use national roaming to cover rural areas. For example operator A could use operator B's network in some rural areas whereas operator B could use operator's A network in other rural areas. Such an agreement would lead to a reduced CAPEX and OPEX for both the operators.

The drawback of national roaming is that due to a lack of QoS differentiation between two operators in national roaming, the competition would be reduced. This is one of the reasons why regulators sometime allow only temporary national roaming agreements, to favour new entrants in a short/medium term, but at the same time to guarantee competition in a medium/long term.

2.4 Mobile Virtual Network Operators

Mobile Virtual Network Operators (MVNOs) are network providers that do not own spectrum and the radio network with which they serve their customers. Some of the MVNOs own the core network; some others only act as service provider to the end users and focus on activities like marketing and strategy. In [L08] it is noted that the number of MVNOs in Europe has increased a lot in the last past years and they are characterised by different business models and are targeting different segments. In general, the MVNO model is perceived positively by the regulators; as a matter of fact in some markets the regulators are even mandating MNOs to open up their network for MVNOs. The reason for this positive perception is that MVNO usually boosts competition, as the value proposition of MVNOs is based on a different tariff and marketing model. From a technical point-of-view, different QoS is not easily achieved.

2.5 RAN sharing

With RAN sharing two or more service providers share the same RAN i.e. base stations and infrastructure. The RAN could be managed by a third party mobile network operator, or one of the mobile service providers could act as a mobile network operator. Costs for leasing the infrastructure could be equally shared by the different operators or divided as a function of the number of users or of the average traffic.

The main value of RAN sharing is the reduction in CAPEX (for example equipment, backhauling, site acquisition and similar costs) and OPEX (for example operation and maintenance, electricity and similar costs) for the mobile service providers willing to share their mobile network. As a direct consequence of the higher margins, the mobile service providers could extend the coverage to new areas, for example rural ones, where otherwise mobile network deployments would be uneconomical. In areas already covered, RAN sharing could speed up the deployment of new technologies, assuming an agreement between all the mobile service providers sharing the same RAN. RAN sharing could also lower the entry barriers for new service providers, trying to enter the market for example targeting a different consumer market segment or a different service.

On the other hand, RAN sharing has also some limitations. First of all, today's technology only supports limited forms of QoS differentiation between operators sharing the same mobile network. Therefore, there would be a high risk of a reduced competition, which would lead to a worse service for the end users and to higher tariffs. This is one of the reasons why in developed countries RAN sharing is usually limited to rural areas, where the margins are lower and there is not much space for service differentiation. Moreover, RAN sharing could also lower the speed of infrastructure upgrade, in case of discrepancies between the technology roadmaps of the different operators sharing the same mobile networks.

2.6 Core network sharing

Core network sharing involves sharing of entities within the core network. This document and indeed the SAPHYRE project as a whole focuses on the RAN, and core network sharing is considered out-of-scope.

2.7 Centralised RAN

Centralised RAN was firstly defined in [CMCC10] as a novel vision for a RAN architecture where the processing traditionally performed in the base stations is moved into a central unit (CU), and connected via high-speed links to spatially distributed transmission points (TP). At the CU real-time centralisation techniques are used to enable resource virtualisation with the goal of reducing the total energy consumption and hardware usage. This vision corresponds to a novel intra-operator sharing solution. As a matter of fact the Base Band Units (BBU) in the pool are shared between different sites (and eventually different Radio Access Technologies), allowing dynamic loading as a function of the user distribution and traffic volume.

The benefits of this vision are clear: an operator could use an intelligent network deployment, by dynamically assigning one of more transmission points to some processing resources in the central unit, as a function of the load. Moreover, the site-footprint would be reduced. CoMP techniques could be used to coordinate the transmissions from/to different TPs, in order to improve the user experience.

On the downside, centralised RAN has some technical challenges that still require some major efforts to be solved. For example, the need for a real-time base band processing could limit the dimension of the coordinated area. The availability of dark fibre is a requirement that could limit centralised RAN based deployments to only some specific regions.

2.8 Fronthaul sharing

The fronthaul infrastructure provides the connection between CU, where baseband boards are pooled, and TPs. Fronthaul infrastructure sharing is therefore similar to backhaul infrastructure sharing. We refer to Section 4.2 for the discussion of fronthaul/ backhaul sharing approaches.

3 Cost analysis

In this section we compare the 8-year TCO of a fully distributed and a fully centralised cellular deployment. We refer to a fully distributed deployment network as to the case where the full protocol stack is implemented at the Base Station (BS) side, whereas we refer to a fully centralised deployment as to the case where the protocol stack is fully implemented in a Central Unit (CU). In other words, in the first case the BBUs are deployed at each site, whereas in the second case a centralised pool of BBUs is serving a common set of transmission points.

3.1 Description of the scenarios

We consider an urban macro-cellular deployment in a typical European large city. We focus on the urban scenario because in this case, in our understanding, a centralised BBU deployment would potentially have the highest impact. We study two different deployments:

1. *Distributed*. Antennas, Radio-Frequency (RF) modules and Base Band Units (BBU) are deployed on-site. Antennas and RF modules are assumed to be deployed rooftop, whereas BBUs are deployed in a dedicated room. BBUs are connected to the core network via either a microwave link or with point-2-point fibre connections.
2. *Centralised*. Antennas and RF modules are deployed on-site whereas the BBUs are fully centralised in a CU. More in general, a pool of BBU resources is shared between the different sites connected to the same CU. The CU is connected to the RF modules via point-to-point fibre connections.

In order to use a common nomenclature, we refer to TPs as, in the case of a distributed deployment, the set of co-located antennas, RF modules and BBUs, in the case of a centralised deployment, as the set of co-located antennas and RF modules.

We assume a network with a hexagonal layout, with 10 rings of TPs (corresponding to 271 TPs) each with three sectors and with an inter-TP minimum distance of 500 meters. In the case of the centralised deployment, all the 271 TPs are assumed to be connected to the same CU. We assume a single-Radio Access Technology (RAT) deployment in each site, and in particular we assume a Long Term Evolution (LTE) RAT.

3.2 CAPEX and OPEX analysis

We assess the Total Cost of Ownership (TCO) by looking at the detailed Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) costs. We evaluate the TCO over a period of 8 years assuming an interest of 5% per year, corresponding to a compound interest of a factor 1.48 for the CAPEX and 10.03 for the OPEX.

In the following, we describe the different costs considered for distributed and centralised case and how they have been accounted for the calculation of the TCO.

3.2.1 CAPEX

3.2.1.1 Distributed deployments

We divide the CAPEX in site construction costs, TP costs and backhaul costs.

- *TP site construction costs.* It includes site clearing and levelling, earthworks, tower construction, cabling, installation of electricity generators and air conditioning, security protection. We note that the costs for site construction can vary considerably as a function of the footprint of the equipment deployed. We will reflect this factor by considering different values for the site construction costs.
- *TP hardware costs.* We consider a 3 sector case with 4 antennas per sector (one radome with 2 cross-polarised columns), one RF module with a 40 W amplifier driving each antenna, and a BBU supporting a 20 MHz LTE deployment. Multi-Input Multi-Output (MIMO) with up to 4 antennas is supported.
- *Backhaul costs.* We consider two types of backhaul: a traditional one based on microwave links and a fibre-based backhaul.
  - For the microwave case, we consider a typical tree-topology, with realistic assumptions about the type of devices deployed and the installation costs.
  - For the fibre case, we consider a point-2-point (P2P) connection between each TP and the CU via a Common Public Radio Interface (CPRI). These optical connections can be realised with a wavelength-division multiplexing (WDM) technology. We assume a logical star-topology between CU and TPs, implemented by deploying for each TP a fibre-cable of length equal to the minimum TP distance plus a 50% fibre deployment margin. For example under the assumption of a 500 m minimum distance between TPs, we assumed to deploy 750 m of fibre-cable per TP. We assume a duct-reuse of factor of 0.5, and we consider two different deployment strategies
    1. The operator deploys the fibre, with a cost for new digs that is about 10 times the cost for duct-reuse. In other words, under the above assumption of 0.5 duct-reuse, and assuming a cost c for new digs, the cost per meter is given by

       $$0{,}5c + 0{,}5c/10 \ \text{[EUR/m]}$$

       where c is chosen as an average between different deployments in Europe.
    2. The operator leases the duct and blows the fibre cable at a cost of $c/10$. The cost for duct-lease has been chosen as an average between different real deployments in Europe. Note that in this case the deployment would also involve an OPEX cost, but we listed it here for clearness of presentation.

We also consider the costs of the electronic for terminating the fibre connections at both the TP and at the CU side, mainly given by Small form-Factor Pluggable (SFP) transceiver hardware at both ends of the fibre connection.

3.2.1.2 Centralised deployments

Together with TP site construction costs, TP hardware costs and backhaul/fronthaul costs, in the case of a centralised deployment we also need to account for the CU site construction costs and CU hardware costs.

- *TP site construction costs.* Differently from the distributed case, in this case we do not need to account for the costs for setting a separate room for the BBUs and the related electricity generators and air conditioning costs. Therefore the site construction costs are generally lower in the centralised deployment case than in the distributed deployment case.
- *TP hardware costs.* Differently from the distributed case, here we account only for the costs of antennas and RF modules.
- *Fronthaul costs.* Due to the high-data rate and low-latency requirements, here we consider only a fibre-based backhaul, for which the same assumptions made for the distributed case hold. The only difference with-respect to the distributed case is given by the deployment of a switching/routing device at the CU side, which routes the I/Q samples and the control information between the specific BBU and TP.
- *CU site construction costs.* We assume three times the cost of a TP site. Note that this cost can be reduced by exploiting the reduction in hardware foot print obtainable by exploiting the BBU pooling gain.
- *CU hardware costs.* At the CU we account for the cost of the BBU pool. This cost is modeled by assuming the cost for each BBU to be the same as the one of BBU accounted in the distributed case. The total number of BBUs in the pool is calculated assuming a pooling gain. In other words we assume that due to the different instantaneous traffic loads in the different TPs connected to the same CU, we can reduce the total number of BBUs in the pool.

3.2.2 OPEX

3.2.2.1 Distributed deployment

We divide the OPEX in site rental costs, maintenance costs and electricity costs.

- *Site rental costs.* We assume a value taken from a real deployment in a major European city, averaged with respect to the different costs in the urban area. We emphasise that site rental is usually one of the main components of the TCO.

- *Site maintenance costs.* We estimate the TP maintenance costs, by assuming the average maintenance costs being a fraction of the CAPEX of the corresponding hardware components at the TP side. The value of the fraction has been taken from real case studies.
- *Site electricity costs.* We use some energy consumption values taken from real-world base-station deployments, assuming a single RAT, LTE as described in Section 3.1.
- *Fibre maintenance costs.* We only assume maintenance costs for the SFPs at the fibre ends, calculated in the same way as the TP maintenance costs. We do not assume any maintenance cost for the fibre cables, as this cost is usually small.
- *Backhaul maintenance costs*, e.g. for microwave backhaul solution, calculated as a fraction of the CAPEX as from above.

3.2.2.2 Centralised deployments

- *TP site rental costs.* For the centralised case the cost for TP renting are calculated assuming a reduction with respect to the distributed case in the range of [0%, 50%]. This reduction accounts for the (in general) reduced radio access footprint of a centralised deployment over a distributed deployment.
- TP *maintenance costs.* The TP maintenance costs are calculated as in the distributed case, with the difference that BBU maintenance costs are accounted at the CU side.
- *TP electricity costs.* We assume that at the TP side there is a 30% energy reduction with respect to the distributed case. While we acknowledge that the exact energy reduction value is still under investigation, we think that 30% represents a reasonable number for this analysis.
- *Fibre maintenance costs.* Calculated in a similar way as in the distributed case, with the difference that in this case we also account for the maintenance of the switching/routing device described in Section 3.2.1.2.
- *CU site rental costs.* We assume three times the cost of a site rent for a distributed deployment. Although we do not have access to numbers from real-world deployments (networks using centralised RAN deployments have yet to be deployed) a factor of three seems to be realistic.
- *CU hardware maintenance costs.* At the CU we account for the maintenance costs of the BBU pool. The maintenance cost is calculated as a fraction of the CAPEX cost, accounting also the pooling gain.
- *CU electricity costs.* We assume that at the CU side electricity costs are about 50% of the total electricity accounted for the TPs. We also consider the electricity reduction obtainable via dynamic hardware loading that further reduces the above 50%.

3.3 Evaluation and discussion for the intra-operator sharing case

As a starting point for the inter-operator sharing analysis, in this section we present the 8-year TCO outcome of the single-operator case.

Between the different cost factors described in Section 3.2, we recognised that the TCO difference between distributed and centralised deployments, is mainly function of the following factors: TP site construction costs, TP site rental costs, backhaul costs, and pooling gain. As the research activity about centralised deployments has only very recently begun, we are not yet in the position of assessing the exact cost differences. For example, the benefit of pooling gain has not yet been fully quantified. Moreover, these costs are often a function of the specific deployment under consideration. For example, the duct-reuse factor, that plays a major role on the assessment of the backhaul/fronthaul costs, assumes very different values in different countries. Therefore, we decided to evaluate the TCO using meaningful ranges of the above-mentioned factors. More specifically:

- Due to the reduced site-footprint, TP site construction costs have been assumed to be between 0% (worst case) and 25% (best case) lower for centralised deployments than for the distributed deployments.
- Again, due to the reduced site-footprint, TP site rental costs have been assumed to be between 0% (worst case) and 25% (best case) lower for centralised deployments than for the distributed deployments.
- The duct-reuse factor has been considered between 0 (worst) and 1 (best case).
- The benefit of dynamic-pooling gain has been considered to be between 0% (worst case) and 50% (best case). We note that a given dynamic-pooling gain benefit involves a corresponding CAPEX reduction on the BBUs pool cost and an OPEX reduction on maintenance and electricity costs.

In Figure 1 and Figure 2 we assess the 8 year TCO under the worst case assumptions (0% TP site construction costs reduction, 0% TP site rental costs reduction, duct-reuse factor = 0, pooling-gain = 0%) and under the best case assumptions (25% TP site construction costs reduction, 25% TP site rental costs reduction, duct-reuse factor = 1, pooling-gain = 50%). We consider three deployments: distributed deployment with traditional microwave backhaul, centralised deployment with fibre fronthaul and distributed deployment with fibre backhaul. We note that different values of the main cost factors can lead to completely different conclusions for the TCO. For example, while in Figure 2 (best case assumptions), centralised deployments lead to a clear reduction of the TCO, in Figure 1 centralised deployments have the highest TCO. Therefore, a conclusion on the best architectural solution can be taken only under detailed assumptions about the specific market in which that architecture will be deployed.

In Figure 3, Figure 4 and Figure 5 we study the effect of the three main factors (TP site construction costs reduction, TP site rental costs reduction, duct-reuse factor) on the TCO of the centralised deployment case, assuming average values for the other factors. We observe that site rental costs and backhaul/fronthaul fibre costs have a very big impact on the TCO.

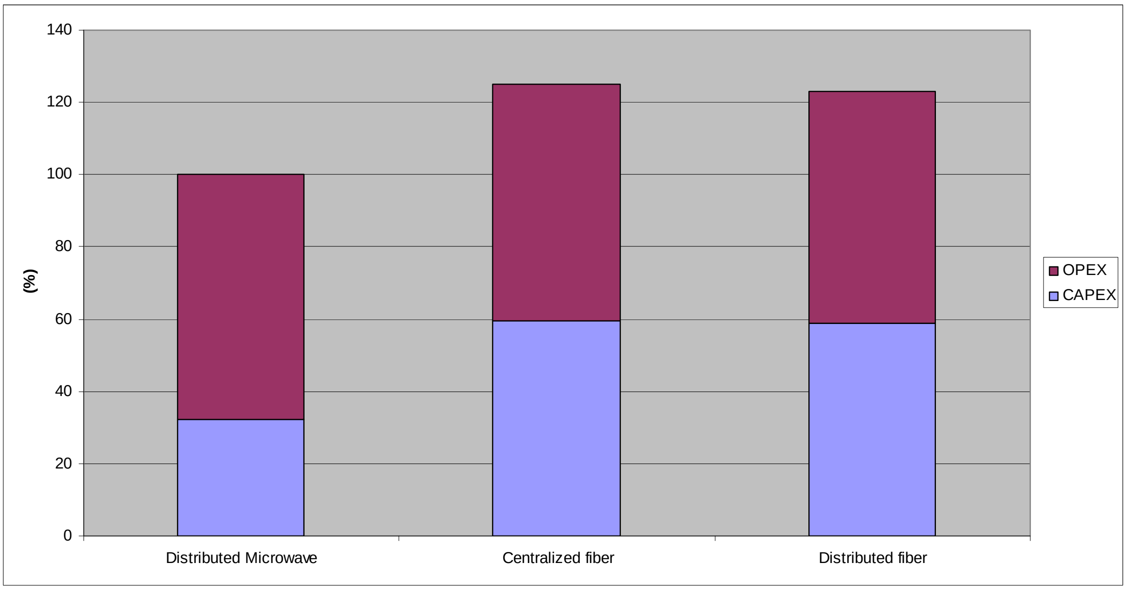

Figure 1: 8-year normalised TCO assessment under the worst case assumptions (0% TP site construction costs reduction, 0% TP site rental costs reduction, duct-reuse factor = 0, pooling-gain = 0%).

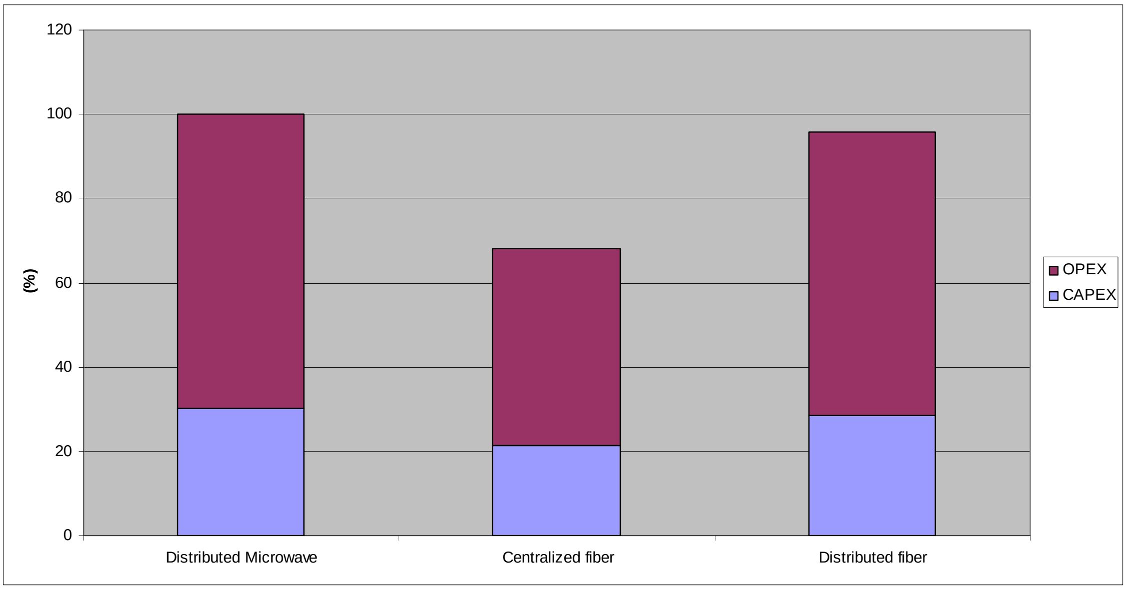

Figure 2: 8-year normalised TCO assessment under the best case assumptions (25% TP site construction costs reduction, 25% TP site rental costs reduction, duct-reuse factor = 1, pooling-gain = 50%).

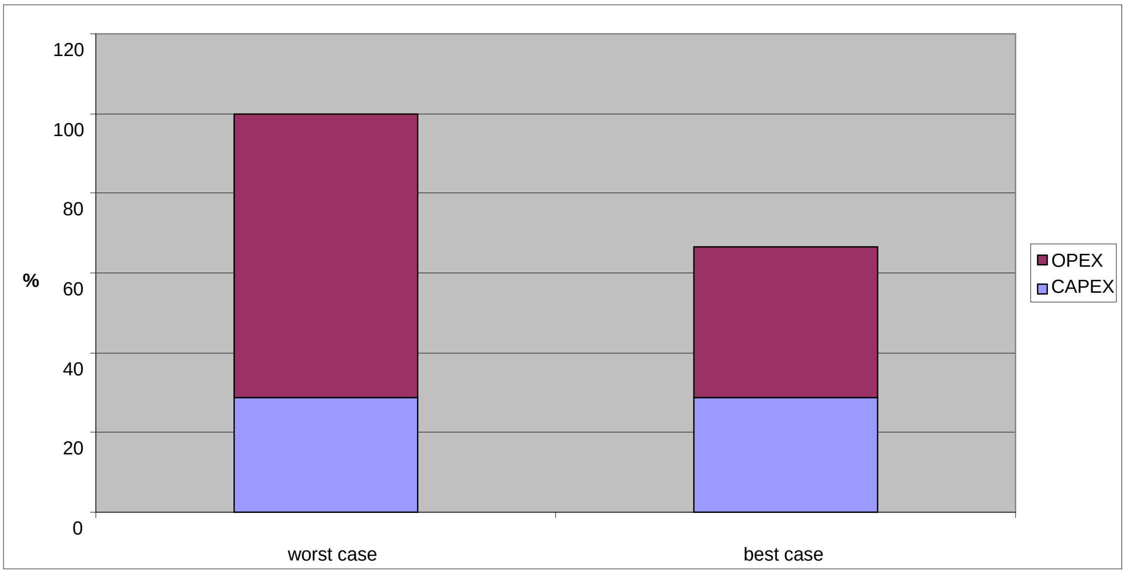

Figure 3: 8-year normalised TCO assessment for the centralised case, under the assumptions of 25% TP site rental costs reduction, duct-reuse factor = 0.5, pooling-gain = 25%. On the left and on the right side we consider respectively 0% and 50% TP site construction costs reduction with respect to the distributed case.

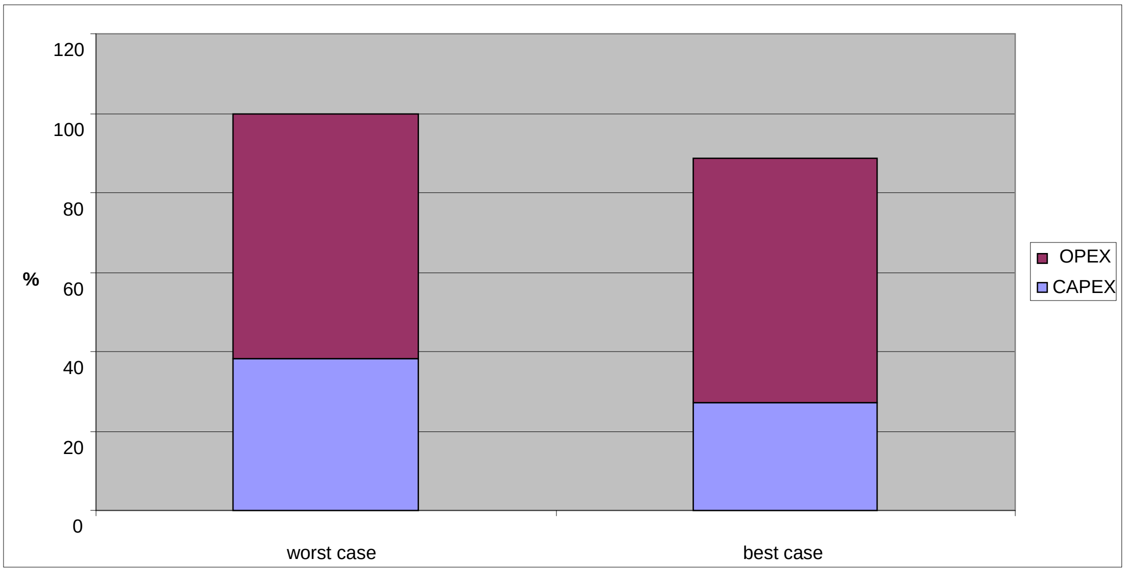

Figure 4: 8-year normalised TCO assessment for the centralised case, under the assumptions of 25% TP site construction cost reduction, duct-reuse factor = 0.5, pooling-gain = 25%. On the left and on the right side we consider respectively 0% and 50% TP site rent costs reduction with respect to the distributed case.

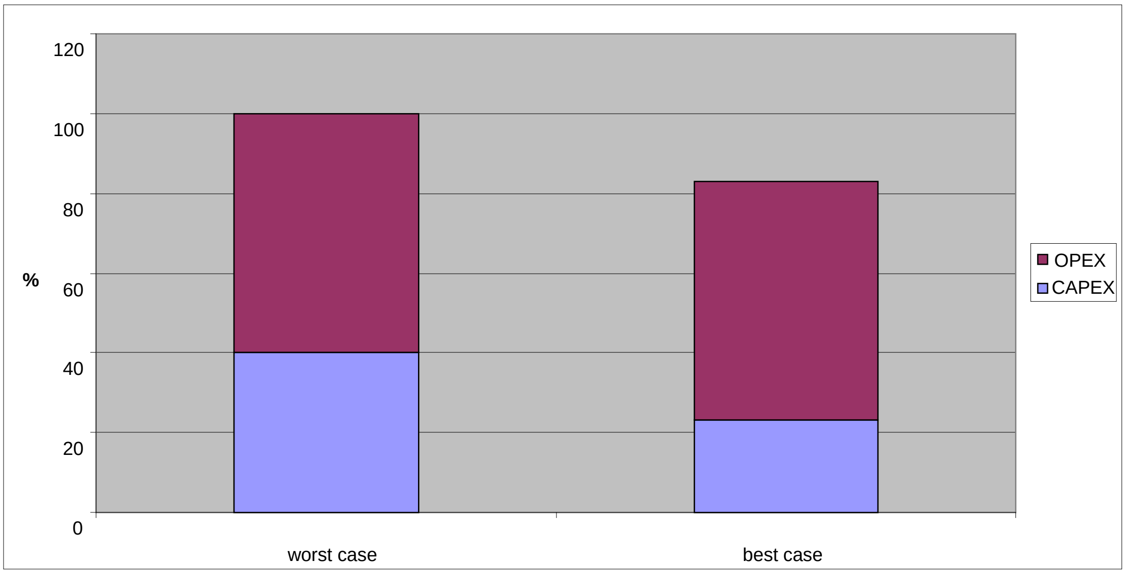

Figure 5: 8-year normalised TCO assessment for the centralised case, under the assumptions of 25% TP site rental costs reduction, 25% TP site rental costs reduction, pooling-gain = 25%. On the left and on the right side we consider respectively duct-reuse factor = 0 and 1.

3.4 Extension to the inter-operator sharing case

In this section we extend the analysis carried out in Section 3.3 to the case of inter-operator sharing. We focus on the centralised deployment[2] under the assumption of two-operator sharing. More specifically, we assume:

- Passive sharing (see Section 2.1 for the definition of passive sharing). More specifically, we assume that the two operators are sharing site/location, mast and cooling units without sharing antennas and RF modules. We consider a 10% increase of the TP site construction costs and a 10% increase of the TP site rent costs, with respect to the single-operator case. These costs are equally divided between the two operators.
- Duct sharing. In particular, we consider two sharing possibilities. In the first one two operators equally divide the costs for duct sharing, but use different fibre cables and therefore different SFPs. In the second one, an operator leases the duct to the other operator. Also in this case, the two operators deploy different fibre cables and different SFPs.
- We assume that the CU is not shared, due to the following observations. First, we observe that the two operators have networks with symmetric traffic distributions (for example morning time peaks in business areas whereas afternoon/evening time peaks in residential areas) and therefore we do not

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[2] We note that under the assumption of distributed architectures with inter-operator sharing, the TCO analysis would have led to very similar results, in particular because we did not consider CU sharing.

expect any gain from dynamic loading across the two operators. Second, we believe that sharing the CU would involve potential issues with subscribers' data privacy and security. Therefore, we model the two CUs as 2 kilometres far apart, which involves an additional 1km of fibre duct for each operator.

In Figure 6 we give the 8-year (normalised) TCO under the assumption of two-operator sharing. As a baseline we consider a centralised deployment with fibre backhaul, as the one considered in Section 3.3. For the sharing case we assume that the two operators equally divide the costs for the shared infrastructure and equipment, which corresponds (for example) to the case of two dominant players in the market. We observe that sharing involves a major TCO reduction.

In Figure 7 we give the 8-year (normalised) TCO under the assumption of fronthaul duct leasing. More specifically, the TCO on the left side is the reference one, obtained by assuming equal sharing of the infrastructure and equipment costs (same as in Figure 6). The TCO on the centre is the one of the operator (operator 1) that deploys the fronthaul network and leases the duct (leading to a positive OPEX entry) to the other operator. The TCO on the right side is operator 2 that leases the duct from operator 1. By comparing Figure 6 with Figure 7 it is clear that duct leasing is convenient for operator 2, but not for operator 1.

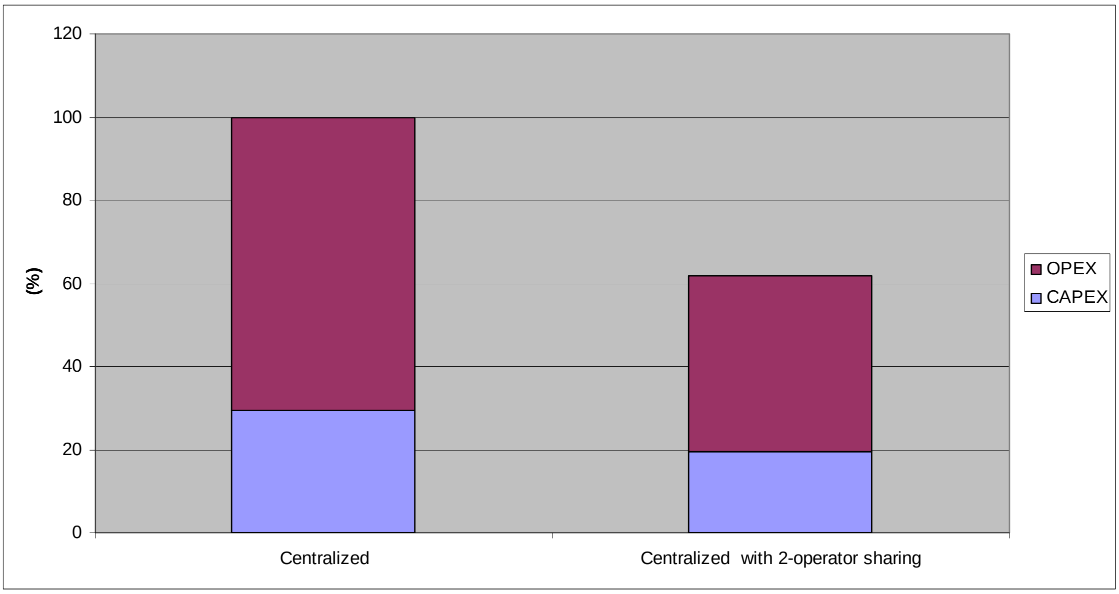

Figure 6: 8-year TCO under the assumption of two-operator sharing.

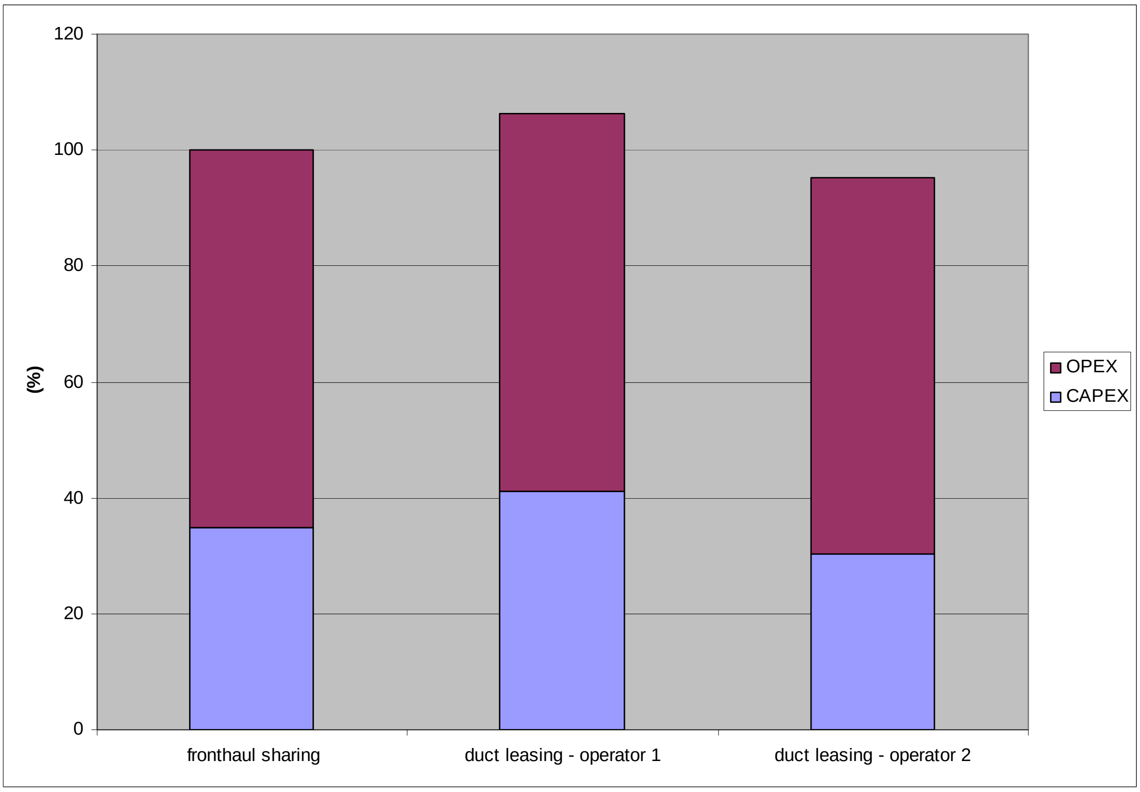

Figure 7: Fronthaul sharing vs. duct leasing.

4 Impact of regulations on centralised RAN deployments with inter-operator sharing

The goal of this section is to give a brief summary of the main implications of regulations on the architectures analysed in Section 3.4. Note that we will focus on the case of inter-operator sharing, as for the case of intra-operator sharing the role of the regulator is clearer and has already been analysed in [SAP12].

In Section 3.4 we stated that inter-operator sharing in the framework of centralised RANs can refer to one or more of the followings: passive sharing, fronthaul sharing and CU sharing. These cases will be analysed in Section 4.1, 4.2 and 4.3, respectively.

4.1 Impact of regulations on passive sharing

Passive sharing is already diffused in traditional distributed deployments [HEAV07] and in some markets even mandated. With respect to the distributed case discussed in Section 2.1, we do not see any major difference that would lead into a need for regulation changes.

4.2 Impact of regulations on fronthaul sharing

An optical-based fronthaul is a requirement for the deployment of centralised RANs, as it provides the required high throughput and low-latency. On the other hand, fibre availability can be scarce is some markets and this can have a major impact on the TCO, as shown in Figure 5. In Section 2.2 we have already introduced fibre sharing in the context of backhaul sharing, as a way to lower the CAPEX costs. In the following we will extend the analysis in Section 2.2, in the context of fronthaul sharing.

We distinguish the following four approaches for fronthaul sharing:

1. Two or more operators *share the duct* each blowing its own fibre-cable. We emphasise that duct sharing is already implemented by many operators (see for example [CSMG01]). In [CS08] a model is proposed where the duct is shared on the basis of an “open access”. Moreover, the European Union gave some guidelines for duct sharing in [EURO08].
2. Two or more operators *share duct and fibre-cable*. This type of fronthaul sharing could be very effective for a regulator to either favour a greenfield fibre deployment or to incentivise some new entrants to enter in a market where the optical-infrastructure belongs to the incumbent operator. We refer to [CS08], for more details and study cases of this sharing approach.
3. One operator deploys the duct and one or more operators *lease the duct*, and each operator blowing its own fibre cable. We refer for example to [CS08] for an example of duct lease approach. The regulator’s role in this case is very critical. As a matter of fact duct lease costs should be regulated in order to favour the

entrance of new players but at the same time without harming the incumbent operators, that usually deploy the fibre network.

4. One operator deploys duct and fibre and the other operators *lease the single fibre cables*. We observe that with respect to the duct lease case, fibre lease is more appealing for operators that need a limited fibre availability. From a regulator perspective, the activity is very similar to the one already discussed in the previous bullet about duct leasing.

Beside the existence of the different possibilities for sharing approaches described above, in many countries we observe a slow down in the deployment of new ducts [ADL10], due to the difficulty to find an agreement between the different market players. As a matter of fact, on one side incumbent operators see a risk in terms of “return of investment”, mainly related to the high CAPEX due to the deployment costs. On the other side, the lack of a clear vision from the regulator about the rights-of-use does not help. In such a situation, the only way forward is a joint effort by regulators, central and local governments, operators and manufacturers. For example, [ADL10] describes some possible frameworks created by governments and regulators to foster fibre deployments. A possibility is to aim at cooperation between public and private sectors, where public institutions co-finance private telecommunication operators in a joint venture. Another possibility relies on the concept of “public reseller”, where a public entity deploys the fibre infrastructure and leases it to private operators (see for example [CS08] for the case Stockholm in Sweden). A cooperation between two private entities would be also possible, and today such a situation is mainly observable in the FTTH market (see [ADL10]). A similar solution can be envisaged for wireless operators willing to deploy a broadband fibre backhaul/fronthaul. An example of such a type of solution, is the agreement between and Deutsche Telekom in Germany [DT12] .

4.3 Impact of regulations on CU sharing

CU sharing is a sharing solution specific of centralised RAN deployments, and it has not considered in the past by regulators. On the other hand, from a regulation point-of-view this case seems to be similar to the case of computational resources shared in a cloud. Therefore we do not see any need for major regulation changes.

5 Conclusions

We studied intra-operator and inter-operator infrastructure sharing solutions from a TCO perspective, focusing on the benefits and trade-offs of distributed and centralised mobile RAN techniques.

For the case of intra-operator sharing, we considered three different deployment solutions:

1. A distributed RAN deployment with microwave backhaul (as a non-sharing baseline);
2. A centralised RAN deployment with fibre-based fronthaul;
3. A distributed RAN deployment with fibre-based backhaul.

For the case of inter-operator sharing we extended the intra-operator study by focusing on centralised RAN deployments and considering site sharing and fibre sharing. In particular, we studied two cases of fibre sharing: one considering two operators deploying together the fibre fronthaul infrastructure and the other one considering one operator deploying the fibre infrastructure and another operator leasing the duct.

We showed that the benefits of network architectures based on full-centralisation depend on deployment assumptions that differ in specific markets, as for example availability of fibre, site rental cost and site construction costs. These results indicate the need of investigating hybrid centralised/distributed solutions that would allow the same performance benefit of centralised solutions, without incurring in the same costs.

We also showed that infrastructure sharing leads to significant reductions in TCO, in particular in markets where the cost (we expect this is the typical case in Europe) of fibre deployment and the site-rent represents a big portion of the costs.

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