D2.3

Business Modelling and Techno-economic Analysis of Satellite eMBB

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<td>ACPU</td>
<td>Average Cost Per User</td>
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<td>CDN</td>
<td>Content Distribution Network</td>
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<td>COTM</td>
<td>Communications On The Move</td>
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<td>Communications On The Pause</td>
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<td>cRM</td>
<td>centralized Resource Manager</td>
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<td>distributed Resource Manager</td>
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<td>eMBB</td>
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<td>FTTdp</td>
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<td>GEO</td>
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Executive Summary

The SaT5G project is researching areas where satellite technology can provide demonstrable benefits to 5G delivery. It is doing this by defining a range of use cases that appear favorable to the technology. These use cases are investigated technically, in terms of business model and commercially via techno economic analysis. This report describes the methodology used for, and main results of, the business modelling and techno-economic analysis of the use cases.

The methodology developed for performing a business model and techno-economic evaluation, was aimed to be generic in structure, yet was adapted to suit the specific use case requirements. It includes both a qualitative and quantitative evaluation, and consists of the following parts:

1. A definition of the different business roles and stakeholders involved in the integrated satellite-5G solution and identification of the possible interactions between those stakeholders, which leads to the identification of different potential business models. Focus is put on the evaluation of the role of a broker for the management of the complex ecosystem of integrated networks.

2. An evaluation the viability of the business case using a Total Cost of Ownership (TCO) model with revenue assumptions to derive an Average Cost Per User (ACPU) which is compared later to the Willingness To Pay (WTP) of the customer.

3. An assessment of the impact of the innovative technology on the business case. Specifically, the impact of caching technology, network virtualization as well as network slicing are studied. Since the latter concepts remove the direct link between network functionalities and physical resources, a dedicated model is built that allows calculating the cost of a network slice based on a fair allocation of network resources used.

4. An evaluation of the uncertainty that links the model outputs to the inputs, carried out via a sensitivity analysis on the most important data.

This methodology is applied to four different use cases: Edge delivery & offload for multimedia content and MEC VNF software, 5G Fixed backhaul, 5G to premises, 5G Moving platform backhaul. For each use case, a concrete scenario was put forward to quantitatively evaluate the economic viability.

The first use case targets edge delivery & offload for multimedia content and MEC VNF software. It aims at providing efficient multicast/broadcast delivery to network edges for content such as live broadcasts, ad-hoc broadcast/multicast streams, group communications and distributions for software updates for network functions. The main takeaways for this use case are:

- Using satellite multicast decreases the OPEX for the integrated SaT5G solution which implies a decrease in the ACPU as well.
- The ACPU is higher in low population density areas than in high population density areas (e.g. France vs Botswana), since we need to install more CDN nodes to cover the sparse households’ clusters while having a smaller number of users.
- The total bandwidth saving increases with the increase of the number of CDN nodes installed because we save more traffic on the “poor” links with installing more nodes.
- Taking the status of the entire network into account reduces the total number of CDN nodes required, hence reduces also the cost.
Secondly, the project investigates using satellite as a fixed backhaul for 5G. This use case is targeted at delivering broadband connectivity where it is difficult or not (yet) possible to deploy terrestrial connections to towers, for example, maritime services, coverage on lakes, islands, mountains, rural areas, isolated areas or other areas that are best or only covered by satellites; across a wide geographic region. The specific scenario that is evaluated quantitatively, includes two rural villages connected via a main road. The main takeaways for this use case are:

- The proposed satellite-5G solution for rural areas is economically viable without caching for a modest bitrate per user and with caching for a good bitrate per user (when comparing to the WTP of the end user).
- Caching popular content to the edge saves from 40% to more than 50% of the OPEX depending on the provided bitrate per user and the caching rate used.
- Installing caching technology is not useful when a low throughput per user in rural areas is expected (lower than 200 kbps).
- The ACPU is very sensitive to the population density variation (i.e. to the number of users).
- The CAPEX is only slightly affected by the variation of caching rate, however the OPEX is very sensitive the caching rate.

Delivering 5G to premises is the third SaT5G use case, in which we aim to use the satellite connectivity to complement terrestrial networks, such as broadband connectivity to home/office small cell in underserved areas in combination with terrestrial wireless or wireline. The main results from our analysis are:

- The SaT5G solution has affordable prices if we compare them to nowadays’ prices for small businesses, taking into account the costs for overhead.
- The ACPU decreases slightly with the increase of the satellite adoption rate as the number of users increases.
- Caching popular data reduces the OPEX and hence the ACPU (from 20 to 25% depending on the caching rate used).
- An agreement with the Satellite Network Operator should be made based on the use of satellite capacity as it is mainly used during day hours only. The broker can play a crucial role in this agreement e.g. the role of the re-seller (the third business model of the broker), if the SNO do not have the intension to sell their satellite capacities in a dynamic way.

Finally, the project investigates backhauling 5G moving platforms, which comes down to providing broadband connectivity to platforms on the move, such as airplanes or vessels. We focus on the specific scenario of broadband on passenger airplanes. The main takeaways can be formulated as: Providing inflight broadband service with a good throughput per user (2 to 5 Mbps) with reasonable prices is feasible thanks to the integration of satellite communications into the 5G network.

- Caching popular data reduces the OPEX and hence the ACPU (from 25 to 32% depending on the caching rate used).
- Different business models are possible for the proposed solution based on who will provide the service to the end user e.g. wholesale model, retail, sponsorship etc....
- Per identified business model many feasible pricing' schemes are identified like Data-based, subscription-based, tiered-bandwidth, per-flight, time-based pricing etc....
In conclusion, in each use case, some affordable opportunities have been identified. Much further work on extending this analysis to more detail and in different countries can be foreseen.

This report presents a prefinal version of the deliverable D2.3, the final version is to be submitted by the end of the project. This prefinal document builds on the previous interim deliverable\(^1\) by including the main results of the different use cases and scenarios. More results and specifically sensitivity analysis will therefore be included in the final deliverable.

\(^1\) Issued as a consortium only document in August 2018.
1 Introduction

1.1 Scope of the deliverable
This deliverable develops the business models and carries out techno-economic analysis based on SaT5G use cases and scenarios defined in D2.1 [1], and business, operational and technical requirements for the integration of satellite and terrestrial networks that were identified in deliverables D2.2 [2].

The goal of this work is to identify the best suited value network configuration and business model for the different use case scenarios identified, and to evaluate these from a techno-economic point of view. The role of the different stakeholders will be described for different scenarios, where the focus lies on the role of the mediator role of the broker (as introduced in D2.2). The business case (quantitative economic analysis of costs and revenues) will be calculated for each of these scenarios, to evaluate the economic viability. This quantitative analysis is based on a lifecycle cost model for deployment of an integrated network, complemented by an allocation model for network slicing.

1.2 Flow of the deliverable
The deliverable mainly consists of different parts:

a. An overview of the methodology followed for the entire analysis process is provided in Chapter 2, as well as a description of the different models developed. Concepts and terminology are explained in this section as well.

b. In Chapter 3, business models of integrated sat-5G networks involving a broker are discussed.

c. Chapter 4 details the network slicing cost allocation model.

d. In chapters 5, 6, 7 and 8, the methodology is applied to the specific SaT5G scenarios for the different use cases that were identified in D2.1.

e. Finally, chapter 9 summarizes the key findings of the deliverable, mainly focusing on recommendations of the business impact of integrating satellite into 5G.

1.3 Relation with other work packages
This deliverable builds upon the use cases and scenarios described in D2.1, as well as on the technical, operational and business requirements described in D2.2. The work done within this WP also take into account the architecture design performed in WP3 - Integrated Network Architecture Design while influencing at the same time some technical decision done in the WP3.

1.4 Context of the work
In the vast majority of 5G deployments traffic will be delivered to the air interface location over land line technology with its unrivalled bandwidth capacity and, in most environments, low unit costs. However, there are a number of use cases where landline delivery is not feasible and a number of geographical environments for further use cases where land line delivery is either economically or practically infeasible. The all-pervasive reach of satellite communications may provide solutions in these use cases, but satellite has by nature lower bandwidth capacity than land line and a higher unit cost. It may therefore prove economically and operationally viable in some circumstances but not others.

The Sat5G project has been all about looking at the technical, operational, financial and business model opportunities satellite might have in 5G delivery. It has done this by defining a range of promising application use
cases and analysing the KPIs of each. The use cases will also be flexed to identify environments where technically and commercially feasible deployment may be achieved.
2 Business modelling for integrated networks: methodology overview

A business model is the conceptual structure supporting the viability of a business, including its purpose, its goals and its ongoing plans for achieving them. All business processes and policies are part of that model. For defining the business models for satellite in 5G, a theoretical background, on which the model is built, was explained in [2] and a general methodology was constructed, following four consecutive, yet iterative, steps:

1. Define the different business roles and stakeholders involved in the integrated satellite-5G solution and the possible interactions between those stakeholders. The different ways of stakeholders’ interaction results in the possible business models (part of this step is executed in D2.2 [2], chapter 3). Focus will be put on the evaluation of the role of a broker for the management of the complex ecosystem of integrated networks.

2. Evaluate the viability of the business case using a Total Cost of Ownership (TCO) model with revenue assumption to derive an Average Cost Per User (ACPU) which is compared later to the Willingness To Pay (WTP) of the customer.

3. Investigate the impact of the innovative technology on the business case. Here, specifically the impact of network virtualization as well as network slicing will be studied. Since these concepts remove the direct link between network functionalities and physical resources, a dedicated model will be built that allows calculating the cost of a network slice based on a fair allocation of network resources used.

4. Evaluate the uncertainty that links the model outputs to the inputs. This will be carried out via a sensitivity analysis on the most important data (and mainly what will be identified later by the mathematical formulation of the model as cost drivers).

This methodology is illustrated in Figure 2-1 below:

Figure 2-1: Business modelling methodology

Note that we do not try to calculate the full Average Revenue Per User (ARPU), since we are not including the profit margins of the different stakeholders involved. However, when comparing the ACPU to the average WTP of end users, we can estimate the resulting profit margins.
2.1 Qualitative business modelling

The business analysis of SaT5G is established in chapter 3 in [2], where the key stakeholders as well as the interaction between them are identified. These interactions are illustrated in a generic value network (figure 3.1 in [2]). Furthermore, the business model including the introduction of a new role “a broker” is described in there as well.

Different business models are possible in the context of integrating satellite into 5G networks. One way of identifying these business models is by analysing how many SNOs and MNOs are involved in the picture and how the satellite capacity is managed and assigned. To simplify the reading, the convention adopted in this section is used to refer to how the satellite capacity is assigned to the MNO. The result is SNO – resource assignation type – MNO. The different business models resulting from this analysis are the following:

- **1–F–1**: in this configuration, one single SNO offers fixed satellite capacity to a single MNO.
- **1–D–1**: the only difference between this case and 1-F-1 is that the resources offered by SNO are dynamic rather than static.
- **1–F–M**: in this scenario, the MNOs have reached a commercial agreement between them to go to the market as a single MNO trying to obtain the best possible deal via the intermediate of a broker. Once the group of MNOs get the fix satellite resources for all of them, it is up to them how to dynamically use it.
- **1–D–M**: in this scenario, the group of MNOs trades with the SNO for satellite dynamic resources. With the dynamic resources, the group of MNOs also dynamically shares the resources.
- **M–F–1**: in this case a single MNO deals with multiple SNOs via the broker to have a fixed capacity. It could be that SNOs have different coverage or different satellite orbit, and the MNO needs from all of them a fixed capacity.
- **M–D–M**: in this configuration a group of MNOs want to share a dynamic capacity from multiple SNOs, as previously explained they deal with a broker to access to the SNOs offers.

Note that the introduction of the broker facilitates the realisation of many of the abovementioned business models especially the cases where the satellite capacity has to be shared dynamically among MNOs.

We refer to chapter 3 for a more detailed description of the different business models for this broker, as well as an evaluation of them.

2.2 Calculating the Total Cost of Ownership (TCO)

Within [1], four use cases for satellite-5G integration were proposed. This step aims to evaluate the economic viability of these use cases, focusing on one specific scenario for each use case. The proposed model considers both the Capital (CAPEX) and the Operational Expenditures (OPEX), designed for converged networks, and considers a planning horizon of 5 years. This model aims to calculate the Total Cost of Ownership (TCO) as well as the Average Cost Per User (ACPU) for the studied scenario. The theoretical background used to build this model is detailed in D2.2 [2] chapter 3 (section Business Case Evaluation). In section 2.2.1, we will discuss in more detail the structure of the model.

2.2.1 Cost Model structure

For modelling the costs of the integrated satellite and terrestrial network in a 5G virtualized setting, four main cost parts need to be taken into account:

- The cost of the 5G mobile network
• The cost of the satellite network
• The cost of integrating satellite communications into the 5G network
• Overhead costs (e.g. marketing, helpdesk, etc.).

The main inputs of the model are the bill of materials (BOM), the number of users, the minimum bitrate per user, the average margin of profit of telecoms operators and the time horizon of the project. Those inputs feed into a cost model that consists of four sub-models in alignment with the network architecture components. The first sub-model is designed for the edge site. It incorporates the CAPEX of the edge components as well as the OPEX of all edge components. The second one models the satellite network used for the backhaul; both CAPEX and OPEX are considered. The third block builds the model of the costs for the 5G core network and the last block in the diagram englobes all overhead costs. After the calculation of the CAPEX and OPEX for all these blocks, the TCO can be derived. Hence, given the TCO as well as the number of users, the ACPU can be derived as an output of the model. This model excludes the cost of the user equipment and the cost of content as well. The structure of the model is presented in Figure 2-2.

Figure 2-2: Cost model structure

2.3 Investigate the impact of innovative technology on the business case: allocation model for network slicing
The overall goal of the business modelling and techno-economic work within the Sat5G project is to define economically viable business cases for integration of satellite into 5G, and this for different use cases. This
incorporates several challenges (linked to the research pillars as described in the project proposal [3]). One of the main challenges, following the technical proposal for incorporating SDN and NFV across satellite networks, is to design a fair cost allocation model for network slicing (Research Pillar I [3]). This section aims first to introduce the concept of network virtualization and network slicing in section 2.3.1 and afterwards presents the state of the art of the cost allocation models. The proposed model of the cost allocation model for network slicing will be detailed in a separate chapter (Chapter 4).

2.3.1 The impact of network virtualization

Network virtualization aims to simplify the network management for the sake of flexibility and easy troubleshooting and relies on different techniques. Software Defined Networking (SDN) is an approach that enables dynamic and programmatically efficient network configuration by splitting the control plane and the data plane and centralizes the control of the network by using an SDN controller. Network Function Virtualization (NFV) moves the network functionalities from hardware into software such that they can run on a range of standard-based hardware which may easily be moved to any locations within the network if needed. The focus of the NFV concept is on reducing the need to add new equipment. This enables more flexibility to scale up or scale down, and more opportunity to innovate, experiment and deploy new services with lower risk [4].

These new emerging technologies being SDN and NFV are jointly beneficial and complementary to each other since they both share the same feature of encouraging innovation, creativity and competitiveness [5] and [6]. Therefore, NFV and SDN together are considered as the key enablers of the network slicing concept. According to [7] “A network slice is viewed as a logical end-to-end network that can be dynamically created. A given User Equipment (UE) may access to multiple slices over the same Access Network (e.g. over the same radio interface). Each slice may serve a particular service type with agreed upon Service-level Agreement (SLA)” [7]. Network slicing allows different service providers with disparate traffic requirements to share the same infrastructure resources.

Network slicing gives Mobile Network Operators (MNOs) the opportunity to open their virtualized networks to vertical segments such as healthcare sector, car manufacturers, intelligent transport providers etc., as well as service providers that lack physical network infrastructure. MNOs need resource allocation models to distribute the resources among themselves and their tenants in a way that first adheres to the SLA agreed beforehand and, second, makes effective use of the network. Resource allocation problem is seen as one of the challenges that face slicing-enabled networks according to many surveys on network slicing [8] and [9].

On the economic side, SDN, NFV and network slicing technologies add more flexibility and easy control to the network management and as such make efficient use of the network resources. Certainly, all these advantages have an impact in term of cost. For example, the use of NFV may reduce CAPEX due to the possibility to deploy VNFs on vendor-independent hardware. SDN can lead to a possible reduction of OPEX because of the easy troubleshooting and maintenance of the network. However, this latter may add more complexity due to the centralization of the network control, hence increasing the signalling traffic on the control plane. Therefore, the influence of these new technologies on the cost of the network must be investigated carefully. Many researchers investigated the impact of SDN, NFV and network slicing from a techno-economic perspective (Table 2-1).
### Table 2-1 SOTA of cost-benefit model for network slicing

<table>
<thead>
<tr>
<th>Paper Title</th>
<th>Studied technology</th>
<th>Proposed model</th>
<th>Methodology and studied use case</th>
<th>Main results</th>
</tr>
</thead>
</table>
| Techno-economic analysis of software defined networking as architecture for the virtualization of a mobile network [10]. | SDN & virtualization | Adaptive cost model for SDN concept | Cost model for SDN networks but this model considers only the CAPEX.  
  German reference network scenario:  
  - Classical scenario: a distributed network architecture with distributed network control.  
  - SDN scenario: a centralized network architecture with decoupled network control from data plane using Open-Flow as communication interface.  
  - Sharing scenario: network virtualization and network sharing between several network operators with a FlowVisor controller. | - SDN and virtualization  
  of the first and second aggregation stage of the network infrastructure leads to considerable CAPEX cost reductions for the mobile network operator.  
  - A 13.81% CAPEX reduction can be achieved for the SDN scenario in comparison with the classical scenario.  
  - A 58.04% CAPEX reduction can be achieved for the SDN based sharing scenario in comparison with the classical scenario. |
| Cost Modeling for SDN/NFV Based Mobile 5G Networks [11]. | SDN & NFV | Cost model | Comparison between Traditional network (with Virtual EPC) and cloud RAN network also with vEPC for Sweden network.  
  However, authors consider only for the OPEX the cost of the power consumption (no maintenance cost nor a failure costs etc..) | - A 63% OPEX reduction can be achieved in comparison with the traditional scenario.  
  - The considered CAPEX could be reduced by 68% in comparison with the traditional scenario.  
  - The considered TCO could be reduced by 69% in Comparison with the traditional scenario. |
| Cost Efficiency of SDN in LTE-based Mobile Networks: Case Finland [12] | SDN | Cost model | Cost model taking into account both CAPEX and OPEX applied to a Finnish reference network. | - SDN decreases the network related annual CAPEX by 7.72%  
  and OPEX by 0.31% compared to non-SDN LTE.  
  - The cost reduction,  
  is a small fraction of the total expenses of a Finnish MNO, but may has an important influence on the profit levels. |
| Life-cycle cost modelling for NFV/SDN based mobile networks [13]. | NFV/SDN | Life-cycle cost (LCC) models | Cost model including both CAPEX and OPEX used to compare non-virtualized network costs with virtualized one with many options.  
  The modelling considers the hardware requirement for each virtualized network function. | - The non-virtualized network has the highest TCO.  
  - Among the virtualized flavours, the setup with 6WINDGate speed-up technology is cheapest |
<p>| Modeling Profit of Sliced 5G Networks for Advanced Network | Network slicing | Revenue model | Multi-Objective Optimization Problem (MOOP) to increase operator Profit: mathematical optimization. | - Novel methodology of modeling profit generated by 5G network slices. |</p>
<table>
<thead>
<tr>
<th>Paper Title</th>
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<th>Methodology and studied use case</th>
<th>Main results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Management and Slice Implementation [14].</td>
<td></td>
<td></td>
<td></td>
<td>• The expenditures and revenues of a network can be estimated according to its slice properties, such as KPI requirements and service prices.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Based on this, the slice implementations can be optimized to maximize the profit.</td>
</tr>
<tr>
<td>Network Slicing as a Service: Enabling Enterprises’ Own Software-Defined Cellular Networks [15].</td>
<td>Network slicing</td>
<td>Business Model and Service Model For NSaaS</td>
<td>Used a detailed process of NSaaS concept by typical examples, together with the configuration process, product management of NSaaS and management APIs for customers</td>
<td>Detailed business and service model for the NSaaS concept that help operators to offer tailored end-to-end cellular network as a service</td>
</tr>
</tbody>
</table>
These researchers focused on the quantification of the cost saving resulting from the use of SDN and NFV [10]-[13], but none of them tackled the cost model for network slicing. For example, [14] presented a revenue model for network slicing based on a Multi Objective Optimization Problem (MOOP) and [15] proposed a new business and services model for network slicing as a service. There are, however, no papers that focus specifically on how the costs of sliced networks should be shared. For example, how much exactly does an eMBB slice cost that requires a big network capacity compared to an uRLLC slice that is very sensitive to latency? How can a network infrastructure provider dimension slices effectively considering the hardware requirement of each slice such that he can reduce costs and maximize revenues? Though they are very interesting research questions, to the best knowledge of the authors, there is no paper available so far that models the allocation of the network costs to the different slices.

Cost allocation models are built using two main components: the cost model of the sliced network and the hardware requirement of each network slice. Both parts are indispensable for any operators in order to ensure a fast Return On Investment (ROI). To this end, we propose in chapter 4 our proposal for network slicing cost allocation model.

2.4 Sensitivity analysis

One of the famous definitions of sensitivity analysis is: “The study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input” [16]. Therefore, any model is built on many assumptions, which means a lot of uncertain input parameters. Hence, the goal of the sensitivity analysis is to determine the impact of these parameters on the outputs of the model. After identifying these parameters, we should discard the parameters with a marginal impact and give an extra attention to the important ones.

Moreover, we should make a clear distinction between uncertainty and sensitivity analysis. Uncertainty analysis quantifies the uncertainty of a random variable. This can be an input to a scientific model, an intermediary variable or even the model’s output. Sensitivity analysis on the other hand studies the impact of the uncertainty of the different inputs on the uncertainty of one of the model’s intermediary or output variables. It shows how the uncertainty in the output of a model can be apportioned (numerical or otherwise) to different sources of uncertainty in the model input. Both disciplines are closely related but should not be confused.

Figure 2-3 tries to capture this difference. Note that the impact of the input uncertainty on the output uncertainty has two components. The height of the input uncertainty itself as well as how this uncertainty is propelled through the model. Sensitivity analysis is interested in the joint effect of these two components, not one or the other.
Figure 2-3: Uncertainty and Sensitivity Analysis
3 Business models for integrated satellite-5G networks: evaluation of involving a broker

Integrating satellite communication into 5G networks causes management issues. This raises several questions: who bears the risk in case of a failure in the network? How to manage the network of another operator? How to get the best offer for a specific location with specific requirements? How to forecast demand to justify investment? Therefore, a trusted third party, known as an aggregator or a broker, can be the appropriate solution for these challenges.

The concept of the broker is not recent; many business models in literature introduced this role as the solution for multi-stakeholder management. For example, the 5G PPP Architecture Working Group proposes the use of the broker to handle the network sharing in multi-tenancy settings [17]. The 5G PPP working group has clarified this role in his business model brochure for 5G networks, in which they define it as an “Intermediary between OSPs (Online Service Providers) and NSPs (Network Service Providers), and between NSPs in their effort to dynamically establish the most effective solution meeting their needs” [18].

In order to take full advantage of a 5G architecture that enables the integration of the north-bound applications and over-the-top (OTT) services, authors in [19] suggest the use of a resource broker which can be a MVNO, micro-operator, or a joint venture formed by service providers. This role serves customers to provision the required virtual network equipment and slices from the infrastructure providers based on a service level agreement (SLA) in which they define the customers’ requirements. Moreover, authors in [20] introduced the 5G network slice broker in 5G systems in order to allow OTT providers, MVNOs and industry vertical market players to dynamically ask for and lease network resources from infrastructure providers via signaling means.

Researchers cited above introduced the role of the broker in their business model for the purpose of managing the multi-tenancy of 5G networks. Therefore, it is trivial, when we add the satellite operator as a stakeholder in the business model for satellite-5G integration, that we also introduce the concept of the broker here to manage the interaction between the terrestrial and satellite stakeholders.

3.1 The role of the broker

The concept of the broker developed by the SaT5G project is consistent with the layered approach of the ETSI Management and Orchestration (MANO) framework [21]. The Network Service Orchestrator (NSO) provides the highest entry point for network domain administrators (SNO side or MNO side); this allows (re)configuring network and infrastructure resources in a semi-autonomous manner, although it requires technical knowledge of the network substrate underneath. The broker represents the business layer that can automate the resource negotiation between operators and trigger the action of domain-specific NSOs.

In this specific case, a broker is defined as an entity responsible to facilitate the SNO offers to other operators in a simple and easy way. For the MNOs, the broker is a tool to achieve the best deals for satellite resources.

For the best of this analysis, we propose to use a business model of a single broker (more like a stock exchange) to deal in satellite resources, acting as the primary interface between MNOs and SNOs. The SNOs would register offered services with the broker, alongside an asking price. The MNOs then require for services at the broker, with an offered price. The broker shall, for a small commission, match sellers to buyers. This simplifies processes for the operators and should lead to a more optimal allocation of resources. Therefore, in order to automate this
process, the broker develops an algorithm to build its database wherein the SNOs’ offers are registered. This algorithm is illustrated in the sequence diagram in Figure 3-1.

![Sequence Diagram](image)

*Figure 3-1: The broker's internal algorithm*

In the simplest cases, the broker can just run an algorithm performing an optimal resource allocation procedure. In more complex cases, human intervention may be required (as described in section 3.4).

The economics of this process are impossible to quantify exactly, but under the assumption of a market operating efficiently, the extra costs due to the broker should be at least cancelled by the price reductions caused by a more competitive, easy access and large market. In fact, overall net cost savings to all agents in the business network are theoretically possible. The next sections will elaborate further, albeit in a qualitative way. This assessment will first be performed in a generic manner, after which three different business model will be described and evaluated in detail.

### 3.2 Generic assessment of the brokerage

The main advantage of the broker model is the simplification of the trading relationships – typically, terrestrial operators need to deal only with one external entity to obtain satellite resources. Essentially, this means that the purchasing of satellite resources is outsourced. The same argument applies in the reverse direction to satellite operators wanting to sell resources as by reducing barriers to sales the overall accessible market size increases.

To ensure a win-win process, it is necessary that the brokerage service is overseen by an efficient regulatory body, much as stock markets are overseen by governmental financial regulators. Specifically, the broker is conceived to provide a way of abstracting satellite resources to the trading parties, exposing abstract objects that are identified by attributes such as capacity, latency, and service availability across different geographical regions, etc. In this way, the resources that are assigned by the trading process can span across different satellite constellations, as well as different satellite operators.

Using one trusted party for managing the interactions also leads to more security and certainty for the different operators involved. By implementing strong cryptographic codes and advanced network security, the broker can set in place an inherently resilient and secure platform for transactions.

To enable the role of the broker in a heterogeneous network composed of satellite and mobile resources, a first challenge consists in the specification of the interfaces between the different domains (i.e. terrestrial, satellite and broker), which need to provide features for optimized resource allocation. The main requirement that these interfaces have to fulfil is to be flexible enough to allow dynamic resource allocation, to be able to include
feedback on the current status of the satellite backhaul links and enable automatic rescheduling in case of failure. As shown in [22], the adoption of Software Defined Networking and Network Function Virtualization (SDN/NFV) in the satellite network will be key to enable the brokerage concept.

Among interfaces management and high-level features, there are technical constraints that have to be tackled in the satellite system that may limit the choices at certain locations (Figure 3-2):

- Need to repoint between GEO HTS to change SNO (e.g. motorised reflectors, flat panel arrays and fully electronic antennas can address this);
- Different SNOs use different vendor equipment (e.g. a standardised based approach using mostly VNFs can address this, or the broker can take up more responsibility, see further);
- Antennas and systems optimised for GEO operation will not readily work with non-GEO Stationary Orbit (nGSO) satellite system and vice versa. (Flat panel arrays, software defined radios and standardised based modems using mostly VNFs may address this).

The interfaces also need to be designed to enable the trading process. For instance, RESTful web interfaces can be a viable option, although not the only one, to give access to the broker platform. It is worth remarking that the design of the broker entity is a relatively new concept introduced in 5G that can take advantage of previous designs, while at the same time give room to new approaches. If the broker will mediate the requests triggering resource reconfiguration through different domain network orchestrators, other challenges still exist.

After the trading process mediated by the broker is completed, the reconfiguration of both virtualised and physical resources shall take place. As soon as MNOs acquire the requested resources, depending also on the specific service class (eMBB, mMTC or uRLLC) delivered over the 5G technology, the reconfiguration of physical assets in the satellite network poses additional challenges connected to the traffic type that is transported. The adoption of SDN technology has the advantage of enabling the reuse of legacy satellite gateway equipment including existing antenna technology. A more sophisticated approach in line with 5G propositions shall consist of relying on satellite gateway virtualization technology and general-purpose hardware that can be reconfigured to connect different space segments resorting to the enhanced flexibility of NFV. Both approaches require careful evaluation of pros and cons.

Moreover, the broker introduces business and techno-economic challenges. In this regard, the marketplace (bidding models, pricing schemes, etc.) that is implemented by the broker is a crucial aspect to be addressed for delivering a dynamic, flexible tool. When using a model that fits many operators there is a risk that a single transaction is not optimal for the trading parties involved, especially when compared to a process that optimizes each individual transaction. Thus, a trade-off should be made between the benefits of faster configuration and transaction through the broker and individual processes that are more standardized but less flexible.
3.3 Different brokerage business models

The broker can take up different roles based on where his responsibility ends, which results in different business models for adopting brokerage in integrated networks. Based on the lifecycle of the satellite resource reservation, three different options can be identified:

- **Option 1 - the broker as a negotiator**: the broker has the role of matching MNOs’ requests to the SNOs’ offers and helps with the negotiation process between the two operators. The role of the broker ends when the contract of the resource reservation is made between the two parties involved. The broker gets paid by a fee added to this contract.

- **Option 2 - the broker as a leasing company**: besides the responsibility taken in option one, here, the broker can sell or lease satellite equipment to MNOs in order to reduce the time for the MNO to set up a service. In this option, the broker has to collect the equipment from the MNO after the end of the contract if the equipment is leased.

- **Option 3 - the broker as a re-selling operator**: this option englobes the previous two options and adds more “power” to the broker. Here, the broker can help the MNOs to configure the satellite equipment and the OSS and set up the satellite connection. This simplifies the task for the MNOs because they do not require to have the expertise in the satellite equipment to install the satellite terminal and set up the connection. In this
option, the broker can lease satellite capacity from the SNO and share it dynamically between the MNO’s according to their needs and to their traffic pattern.

The three identified business models are presented in Figure 3-3.

![Figure 3-3: Different options for the broker role]

These different options show a difference in the contribution of the broker which can be reflected in the domains’ management as shown in Figure 3-4. For the first option, the broker is playing the role of a mediator and does not have real domain management (case 1 in the figure below). However, for the second role of the broker where he can play the role of a leasing company, he can help with providing the satellite equipment and the installation (case 2). For the third business model of the broker, the domain management limits of the broker are extended to the management of the hub infrastructure since he plays the role of a re-seller of the satellite capacity and needs to manage the satellite resources.

![Figure 3-4: domains’ management for SaT-5G case]
3.3.1 Brokerage business model 1: the broker as a negotiator

In the first brokerage business model we propose, the broker acts as a pure negotiator between MNOs and SNOs: he has the overview of satellite supply and terrestrial demand and matches both as optimal as possible.

In order to get the best SNO offers, the MNO addresses the broker with specific resource requirements (e.g. type of satellite connectivity (LEO, MEO or GEO), bandwidth, time limits, QoS (quality of service) class, and geographic coverage). After having received the request from the MNO for specified resources, the broker gets quotes from all the registered SNOs, and runs an internal algorithm to match the MNO’s needs with the SNOs’ offers. Then, the broker reports the best quote to the MNO or reports that SNO offerings meeting his resource requirements are not available. In the first case, in which resources are available, the MNO can decide to either accept, hence sends back to the broker a confirmation to reserve the resource and make the contract or refuse the offer. In the second case, it is possible that the MNO decides to request different resource requirements or finish the negotiation process. The messages exchanged between the MNO, the broker and the SNO are presented in the sequential diagram in Figure 3-6. It is clearly shown here that the broker has significantly simplified the trading process for both actors, as the MNO only has to approach one party instead of multiple SNOs.

In this option, the benefits of the broker are centered around handling of negotiations and simplifying the interactions between the different network operators. As such, the broker helps not only to reduce the time-to-market for the MNOs, but also to increase the efficient use of the satellite resources.

However, the main challenges in this specific role of the broker are the compatibility of the satellite equipment and the best offer selected by the MNO and the specification of the interfaces connecting the trading parties, as described in section 3.2. Furthermore, as this brokerage business model only speeds up the negotiation process, it might be less suitable for dynamic service requests because the broker has no access to the satellite capacity itself in order to share it dynamically unlike the third business model 3.3.3.

The SNOs services applicable within this broker’ option are the “Service based” (satellite Link as a Service, sLaaS) and the “Data pool” (satellite Infrastructure as a Service, sIaaS). The full description of these two services are discussed in section 2.1 of D2.2 [2].

The Business model of Canvas (BMC) of the broker role within this option is shown in the following figure:

![Figure 3-5: BMC of the broker as a negotiator](image)
3.3.2 Brokerage business model 2: the broker as a leasing company

In a second option, the broker role has the same responsibilities of the broker in the first business model, but he can also own and lease satellite equipment, such that the process of setting up the services is also faster.

After signing the contract on the satellite resources reservation between the trading parties, as described in the previous option, the MNO can also request from the broker to rent satellite equipment. If that equipment is...
available, the broker will confirm this to the MNO, who will by his turn arrange with the broker the signing of the lease contract. Afterwards, the broker sends the satellite equipment to the MNO and after the duration of the contract is finished, the broker will collect the equipment from the MNO’s location. The full interactions between the different stakeholders are presented in Figure 3-7.

Figure 3-7: Additional leasing-related interactions for the brokerage business model 2

One of the challenges facing the broker in option 1, is the use of different vendor equipment by SNOs, which could make it difficult for MNOs to accept one of the reported best quotes since they have to change the satellite equipment (especially in short term contract cases). However, in this option, the broker will help the MNO to select and lease the compatible satellite equipment with the selected SNO offer, hence simplifying this process as well. As such, the hassle engendered from the compatibility of equipment and satellite orbit is eliminated. Besides the reduction of waiting time, if the MNO has to receive the equipment directly from the SNO who could be located far away from the MNO’s location compared to the broker who could have many distributed offices (e.g. one office per country).

As a leasing company, the broker might encounter many challenges which could lead also to several risks that have to be studied in advance. In order to understand the challenges and risks of the broker in this business model, we have first to clearly identify his role. The first option is that the broker can buy the satellite equipment from equipment vendors and then re-sell/lease them to MNOs. Here, the broker is facing the risk of an accidental damage or loss of the equipment received under the lease contract. This situation must be specified in a detailed way in the conditions of the contract in order to know who bears the risk and in which circumstances. The efficient use of the satellite equipment and having the right amount stock is another challenge in this specific case. In the second option, the broker represents only an interface between MNOs and equipment vendors. This is hence like the first business model of the broker, but this time the negotiation is between MNOs and equipment vendors and thus has the same kind of risks and challenges. In addition, similar to the first business model, this business model is not suitable for dynamic service requests.
The Business model of Canvas (BMC) of the broker role within this option is shown in Figure 3-8:

![Figure 3-8: BMC of the broker as a leasing company](image)

### 3.3.3 Brokerage business model 3: the broker as a re-selling operator

In addition to the benefits of the broker in the previous two options, the broker within this option can dynamically share the satellite capacity, and hence suitable for dynamic service requests. As such, the satellite capacity can be used efficiently and the time to service can be decreased significantly since there is no need to contact the SNO to lease capacity for short term and with dynamic traffic pattern. Moreover, the use of a broker adds more certainty for the different operators involved. This increased certainty is because the risk of dynamic spectrum allocation is moved to the broker, which means that the involved operators can more easily build their business cases for dynamic capacity offerings. The interactions between the different stakeholders are illustrated via the sequence diagram in Figure 3-9.
The satellite service that suits this role of the broker is “Bandwidth pool (satellite Capacity as a Service, sCaaS)” since the SNO provides raw capacity on the satellite (typically defined in MHz) and the satellite gateway antenna and radio systems, which allows the broker to share dynamically this raw capacity among MNOs. The description of this satellite service is presented in section 2.1 in D2.2 [2].

In this business model, the broker can be seen as a Satellite Virtual Network Operator (SVNOs) since he will lease satellite resources and re-sell/lease them to MNOs. Hence, he has similar challenges and risks as real operators such as resources optimization and setting the right pricing models for optimal resource use and cost recuperation.

The Business model of Canvas (BMC) of the broker role within this option is shown in the following figure:
3.4 Automation opportunities of the negotiation process

In the different broker business models discussed in the previous section, the applicability of an automated process is considered, especially when a time-consuming manual process is required. The next section gives more insights about the different levels of automation the negotiation process can have. Hence, this section describes the impact of notice period and request size on the automation opportunities for the interaction process for negotiation that is common across all three brokerage business models.

Figure 3-11 illustrates how the size of the request for service change dominates the type of process envisaged. It also emphasizes the point that larger and more manual processes requires more notice. These different process types are discussed in the following subsections. The timescales and bandwidths described are indicative and will vary depending on the involved operator and the relationship between them.
1) **Automated processes**

**State of the art**: These types of processes are currently used by satellite network operators for tasks such as:

- Creating, deleting or modifying site details;
- Changing a site from one service plan to another;
- Changing, creating or deleting a service plan;
- Moving capacity to adapt to demand.

These processes typically take a few seconds to minutes to complete, and account for capacity requests within defined ranges of up to a few Mbps. The billing from the SNO to MNO for these changes is automatically updated. The interface to this process is via the SNO’s OSS typically via both human interface (web pages) and machine interfaces using an API such as REST or SOAP.

**Implications for 5G service management**: For planned short-term changes, it is likely that the MNO will want to manage site details and service plans in an analogous fashion to today. For example, consider an MNO resource manager AI wishing to move capacity to a specific need based on predicted or measured traffic levels and change the service plan; the broker is unlikely to be involved in these changes.

2) **Semi-automated processes**

Typically used today for changes which occur less frequently, are more complex and/or involve greater capacity changes. The reseller requests the change via the OSS portal. Some elements such as billing maybe done automatically via a link the ERP system; other elements may require manual intervention. As there is a manual element to this, a larger notice period is needed which might vary from one hour to a few days depending on the nature of the request.

![Figure 3-11: The size of the service change drives the process automation level](image-url)
Implications for 5G service management: This sort of request might be relevant for setting up temporary backhaul links, for example for:

- Planned major outdoor events such as sports or music festivals, or for disaster support;
- Temporary links during construction of major infrastructure;

This process might also be used, for example, to support an MNO expanding its reach into new territories; for example, extending a specific network slice such as an mMTC slice in support of wider ranging sensor networks. This kind of change should benefit from a broker allowing MNOs to obtain the best-fit solution for their changed needs.

3) Manual processes

An example of a manual process today would be the addition of large capacity on a new beam or satellite, perhaps with a specified vendor satellite gateway and terminal system. Processes to do this may well be pre-agreed along with the associated main cost components; however, there will be details to be discussed, agreed, managed and implemented requiring significant manual input.

Implications for 5G service management: Such a process will be probably be required for significant changes to the service provided by the SNO and requested by the MNO and can hence be seen as a new service request. A 5G satellite broker could offer a useful service to allow MNOs to find the capacity they need.

4) Case-by-case negotiations

Case-by-case negotiations are usually only needed for very large orders with specific needs – for example requesting a whole beam using specified vendor hardware and/or a specific gateway location with specific service requirements.

Implications for 5G service management: Such a process will be required for initial service relationship creation and major changes to the service offered by the SNO and requested by the MNO. In this case, the satellite capacity is offered in a fixed way to the MNO.

3.5 Quantitative assessment of the brokerage business models:

As part of the development process for the broker concept, the SaT5G project is building a software emulator to test concepts and algorithms and enable demonstrations. The emulator is intended to suggest a possible software architecture for a real broker. It is implemented in python, with the broker itself operating as a server, and the other agents (MNOs and satellite network operators (SNOs)) operating as clients. The communications protocol is XML-RPC, allowing for future inter-language communications. Initial stages of this software project involve setting up of the clients, servers, message handlers, and logging facilities. Output will be displayed in a semi-GUI fashion, with message passing illustrated with coloured text-mode symbols in a terminal. Later stages (to be reported in D2.3 final) will involve comparison of different internal resource-allocation heuristics.

Typical steps in the negotiation process will be as follows:

1. An action will start with an MNO requesting SNO resources; these will be specified in a standard form (to be specified as part of the development process);
2. The broker will then ask the SNOs for quotes (i.e., offered prices to provide the service);
3. The broker will keep a record of current resource allocations. An algorithm or a heuristic will decide the best allocation of the newly requested resource;
4. The resource will be offered back to the MNO, who will accept or decline.
The emulator will be tested on four scenarios, one per use-case, but which are a specialization of the use-cases, with assumptions made about system sizes, user traffic patterns, link capacities, and other operating parameters. These scenarios are:

1. Use-case 1: 5G Edge delivery. Here traffic will be high but only for short periods. The required satellite footprint is small. GEO satellites will be used;

2. Use-case 2: 5G Fixed backhaul. Here traffic will be for long periods, but only at moderate capacity. The required satellite footprint is small. Again, GEO satellites will be used;

3. Use-case 3: 5G to premises. GEO satellites will be used, since ground stations with tracking are not feasible;

4. Use-case 4: 5G Moving platform backhaul. Periods covered will be up to 15 hours, but at low capacity, and large footprint. MEO, with GEO also if required for coverage.

3.6 Recommendations and future work

The use of a trusted third party such as a broker in heterogeneous networks and inter-domain management solution facilitates the trading relationship between the different stakeholders. In addition, the brokerage role leads to more secure interactions and network management. Moreover, the main advantages of such role are the efficient use of resources, the increase in sales for the sellers and the decrease of costs for the demander (since they got the best quote/price in the market). This chapter presented three different business models, with varying roles and responsibilities for the broker.

Besides the three discussed business models of the broker, one can think of an advanced concept of the broker where the MNOs can also be included as resource sellers, typically when the requester is a third party (e.g. an airline) without any engagement with a specific MNO and have the technical ability to deal and connect to any of them.
4 Cost allocation model for network slicing

A slice is a logical subnetwork defined on top of the physical network to deliver a specific service such as video streaming, IoT applications, etc. This logical network is customized in a way to fulfill a set of KPIs specific to each service: availability, reliability, capacity, efficiency, latency etc. To satisfy those KPIs, different types of network resources have to be reserved for this specific slice.

The network consists of three parts: core network, transport network and radio access network. An E2E slice has to be built taking into account these three different network components. On the core network side, a slice is a chain of virtual and physical network functions. On the transport network part, the slice can be seen as a pipe or tunnel with a specific bandwidth reserved for this slice. Finally, on the RAN side, the slicing is made by means of frequency subchannel reservation. Therefore, the question that raises here, as discussed previously in the introduction, is how to determine the cost of the slice given its exigence in term of these different resource types?

In addition, from a network infrastructure provider point view, a model that allocates cost to the different slices is a useful input to their pricing models. Yet from an MNOs point of view, such a model is also needed in order to identify what the most consuming slices in term of hardware and radio-resources are.

Therefore, we propose a cost allocation model that aims, first, to fairly allocate network costs to deployed slices (services) and, second, to show that network slicing makes more efficient use of the network. The proposed model is built on the following assumptions:

- A network slice will support one specific service;
- A predefined throughput is reserved per service on the RAN and the transport network in a static way;
- On the core network side, a service/slice consists of a chain of (virtual) network functions, such as 5G functions besides physical network functions;
- Virtual network functions (VNFs) are running on virtual machines (VMs), which are in turn executed on servers, and one VM can only host one VNF.

The different building blocks of the suggested model are presented in Figure 4-1. The inputs of the model consist of two different type of inputs:

a) available inputs which are related to the use case (e.g. slice type and the number of users) or can be derived easily from literature (e.g. the chain of network functions per slice); those inputs are represented in the diagram by white boxes;

b) derived inputs from other models that we developed in order to feed this model with the required data; those are represented by the light gray boxes.

Both the cost model of the RAN and the backhaul network and the cost model of the core network used as cost inputs to this model are described in section 2. Moreover, as discussed in section 2.3.1, a complete model that allocates radio, transport and core network resources in the context of sliced network is still missing in literature. In addition, models described earlier do not go in deep into the VNF characteristics level of granularity such as how much memory, processing power and storage each VNF needs to mitigate the overall QoS imposed by the slice. Therefore, building our cost allocation model in the light of an existing resource allocation model is not possible. Consequently, we propose an allocation model for network slicing based on the hardware requirements

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3 The authors are aware that these assumptions simplify the modelling but aim to extend the model to more complex cases in a later stage as a future work.
and the throughput required for each slice. This model aims at allocating the right amount of resources to each slice. This is model is shown in Figure 4-1 below.

![Figure 4-1: Cost allocation model diagram](image)

In order to accomplish this, we have to distinguish between the three types of network resources discussed previously: RAN, transport network and core network resources. The RAN and transport network resources can be reserved as a predefined throughput, priority and latency per slice on the base station and the backhaul network (section 3.1). For the core network resources, this allocation is done in two steps: i) identify the hardware requirement for each 5G VNFs and ii) map these 5G NF requirements onto virtual machines capacities, and then onto servers (section 4.2). Finally, the cost of a slice can be derived using the following formula:

\[ C_{slice} = C_{Thp} + \sum_{i=1}^{K} C_{VNF(i)} + \sum_{j=1}^{l} C_{phNFs(j)} \]

It is worth noting that the step of the hardware requirements identification per NF needs a separate model that we developed.

### 4.1 Cost allocation model of the throughput

For the throughput metric, a predefined throughput is reserved per slice in a static way\(^4\). The cost of this metric can be concluded based on consumed throughput from the overall throughput provided by the base station BS (Equation 4-2). The throughput required by each slice has to be reserved over the transport link as well. Hence,

\(^4\) In the current version of the model we consider that the traffic is static. Yet, in a later stage of the model we will include the dynamicity of the traffic, hence the allocation of the network resources will be dynamic as well.
the cost of the throughput should incorporate a part of the cost of the transport link capacity. Moreover, apart from pure bandwidth requirements, each slice has its own exigence in term of quality of service (QoS), priority level, packet error loss rate, packet delay etc. Thus, for each slice, we reflect the cost of the QoS requirement by means of a weighting coefficient. This latter takes into consideration the required throughput of the slice as well as the needed priority level, thus the latency requirement, as shown in Equation 4-3.

\[
\text{Equation 4-2 } C_{\text{Thps}} = (C_{\text{BS}} + C_{\text{TrCap}}) \times \frac{Q_{\text{co}_s}}{\sum_{s=1}^{N} Q_{\text{co}_s}}
\]

\[
\text{Equation 4-3 } Q_{\text{co}_s} = C_{\text{sharC}} \times \frac{\text{Thps}_S}{\sum_{i=1}^{N} \text{Thps}_S} + (1 - C_{\text{sharC}}) \times (1 - \frac{L_{Sj}}{\sum_{i=1}^{N} L_{Sj}})
\]

With:

- \(N\): number of slices running
- \(C_{\text{BS}}\): cost of the base station
- \(L_{S}\): Latency of the slice \(S\)
- \(Q_{\text{co}}\): weighting coefficient according to throughput and the QoS level of the slice (defined in the next section).

To be able to quantify the QoS weighting coefficient for each slice, a detailed network performance levels are required. Here we adopt the agreed 3GPP traffic types described in detail in [23].

### 4.2 Cost allocation model of core network resources

In order to fairly allocate the core network resource costs to different slices based on the hardware requirements of each slice, we should first find a way to map those requirements to the resources used. This can be done from two different angles: from a data center angle or from a telecom operator perspective. A data center provider tries to find a way to allocate the cost of the data center to the running services/slices to maximize the ROI. A telecom operator, on the other hand, leases the slices from the data center and considers the business model of pay-per-use. A telecom operator hence only needs to know the cost of the service that he wants to offer (hence the cost of the slice that he wants to lease) beforehand through studying the viability of providing such a service. Giving this, the cost allocation model differs according to whom it is designed for. In this section, we will detail the cost allocation model from only a telecom infrastructure provider perspective.

In order to achieve this goal, the infrastructure provider has to allocate the resources into slices according to their requirements in term of processing power, memory and storage capacity. This allocation consists of a mapping process in two steps: 1) mapping the VNFs to VMs and 2) mapping VMs to the data center resources, as shown in Figure 4-2. After this mapping process, the allocation of the network costs to the different slices can be achieved based on the resource consumption of each slice, which is the third step in the cost allocation model.
Step 1: Mapping VNF to VM to estimate resource consumption

In order to accomplish the mapping of the VNFs onto VMs, we should identify first, based on the slice characteristics, the technical requirements for each virtualized network function in terms of computing, storage and networking. Section 4.2.1 below describes our model to identify the hardware requirements of each 5G NFs based on the number of users and the offered traffic by the slice.

Step 2: Resource Mapping: VM to data centre resources to estimate cost

In a second step, the VMs should be mapped to servers and storage resources within a data center, in order to be able to derive the cost of these VMs, and consequently, the cost of the VNFs. Section 4.2.2 provides more details.

Step 3: Allocate the network costs to slices

After mapping the VNFs to VMs and VMs to the data centre resources, the network costs can be distributed among slices based on the resource’s consumption. Section 4.2.3 describes the different option of the cost allocation model.

4.2.1 Modelling the hardware requirements of the 5G NFs

In order to be able to calculate the cost of the network slices, we need to derive the cost of each 5G network function (NF) of which the network slice is composed. The cost of this latter depends on the hardware requirements of this NF (in terms of CPU, RAM and HDD). In this section, we present our model used to quantify the needed hardware requirement for both control and data plane NFs.

4.2.1.1 5G control plane modelling: focus on AMF and SMF

For the control plane we start by modelling the traffic handled by the AMF and SMF, after which we derive the required processing power. The AMF and SMF together form the Mobility Management Entity (MME) in the former evolved Packet Core (EPC) of the LTE network. Therefore, in the approach presented in this section, we base ourselves on the literature that models the control traffic for virtualized MME (vMME).

Our proposed model for the needed hardware requirements for the AMF and SMF (Figure 4-3) consists of two main steps. The first step is to understand the vMME modelling and use it as input to model the AMF and SMF.
This step consists in identifying: i) the most frequent procedures; ii) the frequency of procedure per user and iii) the number of instructions per procedure. The second step identifies the number of exchanged messages per procedure for both AMF and SMF and uses as a driver the overall traffic of the vMME into those two functions. However, when we compare the LTE and 5G service-based architecture, we conclude that there is a difference in terms of the number of messages exchanged between the MME and the rest of the LTE NFs compared to those exchanged between AMF/SMF and the rest of 5G NF. Since AMF and SMF need to communicate with much more NFs than the vMME does (as indicated with the red circles in Figure 4-4), we assume the total number of the messages for the AMF and SMF to be the same as the one of the vMME, but include a correction factor. Finally, we will run a sensitivity analysis on this factor\(^5\).

![Traffic quantification model for AMF and SMF](image)

**Figure 4-3: Traffic quantification model for AMF and SMF**

![LTE VS 5G service-based architecture](image)

**Figure 4-4: LTE VS 5G service-based architecture**

The AMF performs most of the functions that the MME performs in a 4G network, such as terminating the RAN CP interface (N2), NAS signaling, NAS ciphering and integrity protection, Mobility Management (MM) layer NAS termination, Session Management (SM) layer NAS forwarding, Authentication of UE, etc. \([24]\). Giving these functionalities, we can assume that the AMF is a CPU-intensive function.

---

\(^5\) Sensitivity analysis will be performed in a later stage.
The SMF performs the session management functions that are handled by the 4G MME, SGW-C, and PGW-C: allocating IP addresses to UEs, NAS signaling for session management (SM), sending QoS and policy information to RAN via the AMF, downlink data notification, selecting and controlling UPF for traffic routing. The UPF selection function enables Mobile Edge Computing (MEC) by selecting a UPF close to the edge of the network etc. [24].

Based on characteristics of these functionalities, we can assume that the SMF also is a CPU-intensive function and needs a good networking interface.

Therefore, we will investigate for both AMF and SMF how much CPU cores they need in order to serve a given number of users. The main inputs of the model are the most frequent procedures (in terms of message exchange) that each network function executes, the frequency of these procedures per user and per second, and the number of instructions to be executed per procedure message. Those inputs are taken from the vMME modelling in literature. To derive from them the number of instructions that needs to be executed by the AMF and SMF for each procedure, we have to understand how the split of MME functionalities into two functions (being AMF and SMF) is done. To this end, we used the 3GPP specification where both AMF and SMF functionalities are described for each procedure, namely the service request (SR), the service release request (SRR) and the X2-based handover (HO). Afterwards, the number of exchanged messages within a specific procedure for AMF and SMF is used as a driver to divide the number of instructions per procedure message of the vMME. The input of the model, the calculation modules and the outputs are illustrated in Figure 4-3. The input of the model as well as its mathematical formulation are detailed more in the Annex 11.5.

4.2.1.2 The rest of the control plane functions
The remaining control plane functions are the Policy Control Function (PCF), NF Repository function (NRF), Network Exposure function (NEF), Unified Data Management (UDM), Authentication Server Function (AUSF), Network Slice Selection Function (NSSF) and Application Function (AF). Since there is no starting point in literature to dimension those network functions, we analyze their functionalities and we dimension them accordingly.

- The PCF consists of unified policy framework delivering policy rules to control plane functions and has access to subscriber information for policy decisions. Thus, it does not require an important CPU power.
- The AUSF acts as an authentication server, thus it requires a good processing power to elaborate the hashing tasks and the integrity checking.
- The UDM needs first a good memory and storage since it handles subscription management, user identification and it requires enough processing power to support the generation of Authentication and Key Agreement (AKA) credentials and access authorization.
- As NEF offers the exposure of capabilities and events and assures the security provisioning of information from non-3GPP application to 3GPP network, we have to think about how much external application needs to communicate with the 3GPP network but as a first order of estimate we can assume that it does not happen that often thus a modest CPU and storage resources are sufficient.
- A similar reasoning holds for the NSSF that supports the selection of the Network Slice instances to serve the UE and the correspondent AMF, which only happens within the service request procedure.
- For NRF, which maintains NF profile and instances, we can assume that it requires a good processing power and memory as well [24].

In the first version of the proposed cost allocation model, the hardware requirements for these network functions will be determined proportionally and by analogy to other network functions such as, the AMF, SMF, the firewall, the traffic manager etc., since no previous modelling for these NFs is done in literature that can be used as a starting point unlike the vMME.
4.2.1.3 5G data plane modelling

Many researchers model the data plane function (i.e. UPF) for network slicing within the LTE-A and 5G networks using virtualized middlebox network functions [25], [26], [27], [28], [29] and [30]. Middlebox network functions here refer to Network Address Translator (NAT), Firewall (FW), WAN Optimization Controller (WOC), Intrusion Detection Prevention System (IDPS), Video Optimization Controller (VOC) and Traffic Monitor (TM). Authors of these papers have identified a chain of VNFs (which are virtualized middleboxes) per service with specific requirements in terms of bandwidth and latency and hardware requirements per VNF. The chain of network functions per service is presented in Figure 4-5. The main goal of these papers is first to find the best placement of the VNFs in order to optimize the network performance (e.g. minimize the latency) and second to investigate the number of active VNF nodes in specific scenarios in order to optimize the resource dimensioning.

Three main approaches are adopted in literature to dimension the UPF using virtualized middlebox functions. The first method translates the total traffic handled by VNFs to the number of concurrent operations for each VNF and deduce from that the needed hardware requirements [29]. The second approach derives from the middlebox datasheets the required processing per user and given the number of users they deduce the needed CPU and others hardware requirements for each VNF [31]. The third approach defines a CPU-core-to-throughput relationship for each VNF and uses it to calculate the required number of CPU cores per VNF, like the method established in [28].

Since those dimensioning methods use different approaches and different assumptions, we will apply them to a specific use case (see section 5.7) and compare their outcomes and adopt the option that gives the more realistic results that align with other findings in literature.

4.2.2 Mapping virtual machines to data centre resources

Now we know how to translate the VNF requirements into VM capacities, the next step maps these VMs to servers and storage resources. There are three options for this within a data center: i) VM with fixed configuration, ii) VM with predefined categories and iii) Personalized VM according to the need of the NF. The first option was adapted in the model used in [11]; a simple mapping between the blade server resources and the resource offered to each VM is elaborated by dividing the server capacities in an equal way among VMs.

However, this method assuming the same size of VMs is not efficient in term of use of resources, because VMs can be over- or under-dimensioned. For this, the second option with VM with different class or types was suggested. In this second option, the VMs can be classified into classes (for example: small, medium and large) such that the mapping between the VNF and VM can be more effective. Finally, the third option allows to create a personalized VM according the NF requirements. Though this option assigns the required resources to each NF.
effectively, it considers only a static traffic without a margin of safety if the NF would receive more traffic than expected. This option also increases the unused resources and hence raises the question how to allocate the cost of these unused resources to the different slices?

After selecting the suitable mapping option, a server consolidation algorithm that considers the co-location of the highly communicating VMs such as [32] and [33], can be applied aiming at placing the different VMs at the suitable server to reduce data center network traffic and thus decrease the latency for the deployed slices.

For our allocation model, we chose the second option of mapping VMs onto the data center resources, being the predefined categories of VMs. Those categories are presented in Table 4-1.

Table 4-1: VM classification

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>1</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>RAM (GB)</td>
<td>8</td>
<td>16</td>
<td>40</td>
</tr>
<tr>
<td>Temporary storage (GB)</td>
<td>50</td>
<td>100</td>
<td>1500</td>
</tr>
</tbody>
</table>

We consider that each slice S consists of chain of virtual network functions VNFs. In addition, each VNF has its requirements in term of CPU, RAM and HDD. In addition, each VM from categories S, M and L has its own characteristics in term of the same metrics i.e. CPU, RAM and HDD as well.

Now the mapping of VNFs to VMs is determined by the maximum number of VMs required for each metric, and this is done for all the three VM categories. Afterwards, we pick the category that gives the minimum required number of VMs. The algorithm of mapping VNFs to VMs is described in the following table:

Table 4-2: NF to VM mapping algorithm

```plaintext
Algorithm: NF to VM mapping algorithm
Input: Set of slices S= {S_1, S_2, ... , S_N}; set of network functions per slice NF= {NF_1, NF_2, NF_M}; set of VMs with different hardware characteristics VM={S, M, L};
Output: allocated VMs for each slice
1: FOREACH slice in S do
2:       FOR i=1 to M do
3:                FOREACH j in VM do
4:                   vm(CPU)ij=Ceil (CPU(NFi)/ CPU(j)); /* nb of VM type j to satisfy the CPU required by NFi */
5:                   vm(RAM)ij=Ceil (RAM(NFi)/ RAM(j)); /* nb of VM type j to satisfy the RAM required by NFi */
6:                   vm(HDD)ij=Ceil (HDD(NFi)/ HDD(j)); /* nb of VM type j to satisfy the HDD required by NFi */
7:                   vmNFij=MAX (vm(CPU)ij, vm(RAM)ij, vm(HDD)ij);
8:                ENDFOREACH
9:       vmNFi=MIN (vmNFiS, vmNFiM, vmNFiL);
10:   ENDFOR
11: ENDFOREACH
```

After mapping the right amount of resources to each VNF and hence to each slice, the questions that is raised is how the allocation of the core network cost to the different slices will take place?
4.2.3 Allocate network costs to slices

There are two options to distribute the core network costs among the slices. The first option uses the hardware requirements of each slice as a cost driver for splitting the total cost of the core network between the running slices. Hence, within this option, unused resources costs will be covered by assigning them proportionally to the different services/slices based on the cost driver. On the other hand, the second option relies on allocating only the cost of the used resources to its slice and does not consider the cost of unused resources. Hence, for our model, we will adopt the first option.

It can be seen clearly from the description of both the resource allocation model and the cost allocation model that the hardware requirements of each VNF are a crucial input to those two models. Moreover, our model is designed to be used for 5G networks where network slicing will take place as a new emerging technology. Hence, 5G NF are the NFs that form the slice on the core network side. Therefore, the hardware requirements of these 5G NFs are the key inputs for the proposed models.

This cost allocation model is proposed as a way for the network infrastructure provider to be able to fairly distribute the network costs among the different services. The proposed model is based on the calculation of what the service needs as network resources and then distribute the network costs among services accordingly. One can adopt another model to price the network slices like the Pay Per Use model described in the Appendix section 11.6.
5 Use case 2: 5G Fixed Backhaul - reference scenario

5.1 Introduction
This use case consists on providing broadband connectivity where it is difficult or not (yet) possible to deploy terrestrial connections to cell towers, for example, coverage on lakes, islands, mountains, rural areas, isolated areas or other areas that are best or only covered by satellites; across a wide geographic region.

This covers a wide range of scenarios. The following analysis considers three scenarios based on the relative geographical reach of satellite backhaul. The three scenarios are: a) Satellite backhaul to groups of cell towers; b) Satellite backhaul to individual cell towers and c) Satellite backhaul to individual small cells. In all cases the user and control plane data are interconnected to the core via the satellite gateway.

The selected scenario to be studied is scenario a above and referred to in this document, as [SaT5G] scenario 2b. This scenario consists of a satellite backhaul connected to a cell tower located in a rural area in the EU covering two villages about 5km apart connected via a rural main road. The villages are home to 350 families, with an average of three users per home. The predominant traffic on the cell is eMBB (enhanced Mobile Broadband).

For this scenario, the techno-economic analysis aims to realize several objectives:

- Evaluate the Total Cost of Ownership (TCO) of the proposed solution using a TCO cost model (as described in section 2.2);
- Investigate the impact of caching popular content at the edge on the OPEX and TCO;
- Allocate the TCO to the different network services (slices) using the cost allocation model proposed for network slicing (described in section 2.3, and detailed in Chapter 4);
- Investigate the implication of using network slicing techniques on the TCO via comparing the actual 5G core network cost to the cost of the resources needed to deploy the slices;
- Evaluate the uncertainty of the input using sensitivity analysis (e.g. rate of caching...) as described in section 2.4.

5.2 Network architecture
The proposed solution proposed within SaT5G project to provide eMBB service to the selected scenario is composed of:

1. A 5G core network that treats and processes the offered services;
2. A satellite gateway connected to the 5G core network via a fiber connection, which is responsible for forwarding the traffic from the core network to the radio access network (RAN) via a satellite link;
3. A satellite terminal installed near the RAN that receives the traffic from the satellite gateway via the satellite link and sends it to the RAN and vice versa;
4. Finally, a RAN which consists of eNodeBs (evolved Node B, i.e. mobile base stations), responsible of carrying out the traffic from the 5G core to the end user and vice versa.

The network architecture is presented as follows in Figure 5-1:
In the next section we evaluate qualitatively the feasibility of the proposed solution and provide insights into the potential business models that suit the heterogeneity of this solution.

5.3 Qualitative business modelling

Based on the possible business models described in section 2.1 and in section 3.3, the most likely scenario for this case is the 1-F-B in a short-term period. This VNC option consists of one single MNO serving the rural site while dealing in a static way (i.e. static configuration of the satellite capacity) with a broker. This latter deals with multiple SNOs and provides a summary of the best SNOs offers to the MNO, which represents the first option of the broker role described in section 3.3.1. Yet for a long-term period, given a multi-tenancy on the base station, the M-F-B will be the most suitable scenario. This business model allows for multiple MNOs to share the same base station on one site to provide their services. Those MNOs deal with the broker to access to the SNOs offers.

5.4 Quantitative business case evaluation: TCO model

As described in chapter 2, we use a TCO model to evaluate the economic viability of the proposed solution for the selected scenario.

5.4.1 Cost model structure

The main inputs of the model are the bill of materials (BOM), the number of users, the minimum bitrate per user, the average margin of profit of telecoms operators and the time horizon of the project. Those inputs feed into a cost model that consists of four sub-models in alignment with the network architecture components presented in the previous section. The first sub-model is designed for the edge site. It incorporates the CAPEX of the radio access network (RAN), the CAPEX of the satellite terminal, the common CAPEX and the OPEX of all edge components. The second one models the satellite network; both CAPEX and OPEX are taken into account. The third block builds the model of the costs for the 5G core network and the last block in the diagram englobes all overhead costs. After the calculation of the CAPEX and OPEX for all these blocks, the TCO can be derived. Hence, given the TCO as well as the number of users, the ACPU can be derived as an output of the model.
5.4.2 Mathematical formulation of the model
The previous section has presented, from a high-level perspective, the structure of the proposed cost model. In this section, we will detail each sub-model formula used to calculate both CAPEX and OPEX parts. An overview of abbreviations can be found in Table 11-1.

Cost model of the edge site
The cost of the edge incorporates the CAPEX of the RAN, the CAPEX of the satellite terminal, the common CAPEX and the OPEX of all the edge components. The number of equipment needed depends on the dimensioning process of the site, which in turn depends on the bitrate to be provided in the site (Equation 5-1). The CAPEX of the RAN (Equation 5-3) depends on the number of eNodeBs to be deployed, which is the maximum of the number calculated based on the bitrate and the coverage area of the served site (Equation 5-2).

\[ Br_s = N_u \times Br_u \]  
\[ N_{enb} = \text{MAX}(\frac{Cov}{Cov_{enb}}, \frac{Br_s}{BW_{enb}}) \]  
\[ \text{Capex}_{RAN} = N_{enb} \times C_{enb} + C_T + C_{inst} \]  
\[ \text{Opex}_{RAN} = \text{Site}_{rental} + (P_{enb} + P_{ST}) \times C_{watt} + M \]

Furthermore, the CAPEX of the satellite terminal consists of the satellite terminal equipment, which is calculated based on its link capacity with the satellite. The common CAPEX incorporates all common capital costs needed to build the edge infrastructure. Finally, the OPEX of the edge (Equation 5-4) consists of the cost of the power consumption of all the equipment, the cost of the site rental per year and the maintenance costs.

Cost model of the satellite network
The cost model of the satellite network consists of two main parts. First, the CAPEX of the satellite gateway, which is the cost of the equipment and the building required to deploy the satellite gateway. Second, the OPEX of the satellite network (Equation 5-6), which is the cost of the satellite capacity (Equation 5-5), in addition to the cost of the maintenance and the power consumption.

\[ \text{Capex}_{satCapS} = (Br_s + Br_T) \times 12 \times C_{satMbps} \]  
\[ \text{Opex}_{sat} = C_{satCapS} + P_{satGar} \times C_{watt} + M \]

Cost of the 5G network:
For modelling the 5G core network, an estimation of the cost of the core network per Mbps should be made. Given this estimation in addition to the total required traffic, the cost of the 5G core network can be calculated. This model uses results in Table 11-6 about the cost per Mbps for the hardware and the software of the 5G core network.

Additional costs
We have built the cost model using the following assumptions for the additional costs:
- Hardware installation cost is 15% of the hardware costs [34]. The cost of the hardware installation is part of the CAPEX costs and it is expressed by the following formula:

\[ \text{Eq} \text{.5-7 } C_{inst} = 15% \times C_{hw} \]
• Maintenance cost is 10% of the CAPEX costs [34]. Maintenance costs are counted in the OPEX costs.

\[ \text{Equation 5-8} \quad M = 10\% \times \text{CAPEX} \]

• In most cases, the overhead cost is defined as the cost of marketing, helpdesk, human resources, finance etc. According to [35], it is around 22% on top of the sum of the CAPEX and OPEX costs.

\[ \text{Equation 5-9} \quad \text{Ovhd}_c = 22\% \times (\text{CAPEX} + \text{OPEX}) \]

**Total Cost of Ownership (TCO)**

The Total Cost of Ownership (TCO) of the proposed solution is counted as the sum of the CAPEX, the OPEX of 5 years and the overhead costs of 5 years.

\[ \text{Equation 5-10} \quad \text{TCO} = \text{CAPEX} + \sum_{t=1}^{5} (\text{OPEX}(t) + \text{Ovhd}_c(t)) \]

### 5.4.3 Model inputs

Inputs used to run the cost model are presented in the tables in Appendix section 11.2.

In addition, the cost model is based on several assumptions that should be made to have as realistic results as possible:

- Project horizon is 5 years (hence no hardware renewal is anticipated)\(^6\);
- The average revenue per user (ARPU) is the average cost per user (ACPU) plus a profit margin of 11% [36];
- The willingness to pay of rural users is 19 euro: the average European price of a mobile broadband service (including 10 GB of data) is 21.77 euro per month. This price is valid for urban and rural areas. However, if we aim for a 100% of service adoption, this price should be decreased by 15% to be adopted by rural inhabitants as well as non-adopters in urban areas according to a wide survey carried out in the USA [37].

### 5.4.4 Simulation and results

From the mathematical formulation of the model presented in section 5.4.2, we can conclude that the number of users as well as the minimum bitrate required per user are the main cost drivers of our model. First, they affect the dimensioning process, see Equation 5-2 and Equation 5-3. In addition, the OPEX costs (Equation 5-6) are directly driven by the bitrate per site.

In order to generate realistic results taking into account the bitrate per user cost driver, there are three ways to proceed. The first one is to forecast the average consumed mobile data traffic per user (i.e. monthly download volume) in the considered timeframe (2020-2024) and then calculate the bitrate per user that generates this amount of mobile data traffic. The second option is to set an initial average bitrate per user according to the broadband service requirement, namely 2 Mbps. And the third option is to set an initial bitrate per user according to the DAE 2020 target [38], namely 30 Mbps. We can assume that the first case corresponds to a low-end scenario, the second one to a likely scenario and the last one to a premium scenario, and hereafter their description:

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\(^6\) The lifetime of most equipment is almost 5 years thus the lifetime of the project is also assumed as 5 years without a renewal of hardware.
Low-end scenario

This scenario considers the backhaul traffic required to support the traffic to 1050 end-user mobile devices but not any fixed systems in the house such as smart TVs and computers that consume large amounts of data to watch streamed TV. In order to have an idea about the future mobile data traffic, we refer to the well-known Cisco VNI report [39]. It forecasts that in 2021, the monthly mobile data traffic for Western Europe will be 6.5GB per user. To know the user bitrate needed to generate this amount of data, we rely on the Analysis Mason data used in the BATS project report [40]. The calculation considers the number of hours during which the user is active, then it results that each 1GB per month corresponds to an average busy hour data rate of 7.8kbps. For our case, we have 350 families, of 3 devices each multiplied by 6.5 and by 7.8, make therefore a total of 53.2Mbps per site.

Likely scenario

In this scenario we consider the situation where all the traffic to the 350 households is carried by the 5G satellite backhaul. This includes smart TVs and computers that consume large amounts of data to watch streamed TV. In this analysis we, we should stick to the EC requirements, which consider a service as broadband if its speed is more than 2 Mbps [41], [42]. This can be compared to the EC FP7 BATs study in D5.2 [43], that states 1Mbps to 2Mbps is needed for each household during the busy hour in Western-Europe in 2020. For our case, we have 350 families, of 3 users (hence 3 devices) each. If we consider that, the bitrate per user is 2 Mbps, only 80% of users are active users, and the number of active hours is 9, thus, it results in an average busy hour data rate of 630 Mbps per site.

Premium scenario

In order to guarantee a good Quality of Experience (QoE) for the end user, the European Commission (EC) requires a bitrate of 30 Mbps per user for high-speed broadband services, as explained in [38]. Hence, in this scenario we assume that the bitrate per user (3 users per family, 350 families) is 30 Mbps, thus taking into account the active user rate of 80% and the number of active hours of 9 per day, the resulted average busy hour data rate is 9450 Mbps per site.

For the three scenarios, on top of the site bitrate, we might expect 10%-20% traffic and control plane overheads.

5.4.5 Results of business case analysis for the baseline scenario

As a first step, we simulate the proposed architecture for the scenarios discussed previously: the low-end, likely and the premium scenario, based on collected inputs presented above and assumptions discussed in section 5.4.3. Results of the TCO for the three scenarios are presented in Figure 5-2.
The monthly ACPU for the low-end, likely and premium scenarios have been derived: 2.5, 12 and 160 euro respectively. The ACPU for the low-end scenario (50.6 Kbps per user) is very cheap comparing to the willingness to pay (WTP) of the rural inhabitants (19 euro as discussed in section 5.4.3). For the case of the likely scenario the ACPU is not expensive also comparing the WTP. Hence, we can say that the satellite-5G solution is viable for rural areas with a modest bitrate per user. However, if we opt for a good QoE (premium scenario with 30 Mbps per user), the ACPU results in 160 euro, which is way higher than the WTP (especially if we take into account that the ACPU calculated here does not yet include a profit margin for the telecom operators or service providers) restricting this to being deployed to only a very important locations within a network.

In the view of optimizing these results, we examine the resulted cost components in more detail, we find that the OPEX are very high, as clearly observed in Figure 5-2. This is due to the satellite capacity (backhaul) that should be paid monthly. One of the solutions proposed to decrease these OPEX is to cache a percentage of the popular content on the edge and by doing so we decrease the amount of traffic that needs to be carried out via satellite link, in turn decreasing the operational costs (Wang et al., 2014).
5.4.6 Simulation with caching data on the edge to decrease OPEX

5.4.6.1 Caching technology
Tremendous growth of the video content request is foreseen for the next years. According to the Cisco VNI Forecast Highlights Tool, Internet video traffic will be 80% of all consumer Internet traffic by 2022 compared to 73% in 2017, which corresponds to 29.5 EB (Exabyte) per month by 2022 compared to only 8.9 EB per month in 2017 [39]. This growth is driven by the expansion of VoD (Video on Demand) libraries. According to the same forecasting tool, consumer IP VoD traffic will reach 3.8 EB per month by 2022, yet, it was only 2.6 EB per month in 2017.

The traditional centralized networks cannot mitigate this exponential growth of user demand giving the heavy load on the backhaul links and the long latency [44]. In order to accommodate the huge bandwidth requirements resulting from the massive demand of the high-definition video content, new network architectures based on caching strategies have been proposed. Essentially, caching techniques aim to store a duplicated copy of the most popular content in the network edge. In this way, the end user does not have to download it from a central location in the network. Hence caching techniques transform the bandwidth requirement into a storage requirement which reduces latency and increases QoE [45]. Several papers in literature optimize content caching techniques and algorithms [44] and [46].

The main question that should be addressed when a caching-based solution is chosen, is how much data we have to store in the edge. Authors in [47] proved that the Pareto law is valid for video content consumption on the Internet. They found that 10% of the most popular videos on YouTube account for approximately 80% of the views. On the other hand, the 90% of the remaining video content has only 20% of views (the same results were found for Daum (a video service in Korea) as well) [47].

5.4.6.2 Caching scenario specifications
Two reasons are behind the use of the caching technology in this scenario. The first one is to decrease the amount of the traffic that needs to be sent via satellite link, and by doing so, decrease the cost of the satellite capacity and hence the OPEX. Furthermore, caching popular content on the edge will not only solve the issue of increasing demand for bandwidth, but will also decrease the latency of the video traffic, as the content is placed closer to the end users. Therefore, our second reason is to decrease the latency for VOD service.

In the network architecture presented in Figure 5-1, we need to add Multi Edge Computing (MEC) infrastructure on the edge site [48]. The role of the MEC is to cache a percentage of the popular content locally on storages on the edge and to communicate with the base station to receive users’ requests and send back the corresponding content. An intelligent algorithm is there to update the cached data according to the frequency of usage and downloads of new content. We assume that the Pareto law is applicable here (as argued in the previous section). Hence 20% of popular content will be stored and 80% of user video requests are served from cached data. As 80% of the user’s traffic is video (as argued previously in the previous section), and 80% of the video requests can be served from the cached data (which is 20% of the popular content), this results in 64% of the user traffic to be served from the local cache. As this assumption directly affects the OPEX, a sensitivity analysis on the caching rate will be given later. The new network architecture is presented in Figure 5-3 below:
In addition to changes in the network architecture of the proposed solution, there are also changes in the cost model structure. We need to consider in the new model both the CAPEX and OPEX of the MEC deployment. Based on how much data can be cached on the edge, the number of storage equipment and servers required is calculated, and then the cost of the entire MEC infrastructure is derived based on the following equations:

\[
\text{Equation 5-11} \quad \text{Cost}_{\text{MEC}} = \text{CAPEX}_{\text{MEC}} + \text{OPEX}_{\text{MEC}}
\]

\[
\text{Equation 5-12} \quad \text{CAPEX}_{\text{MEC}} = N_S \times C_S + N_{stg} \times C_{stg} + \frac{M_{\text{mg}}}{N}
\]

The main difference between the two scenarios (without and with caching data on the edge) is the cost of the satellite capacity. Based on the number of user requests that will be served from the cached data \( R_{cd} \) (Equation 5-5) becomes the following equation:

\[
\text{Equation 5-13} \quad \text{C}_{\text{satCapS}} = \left( (1 - R_{cd})B_S + B_T \right) \times 12 \times C_{\text{satMbps}}
\]

The model inputs related to this deployment are recapitulated in the table below:

When we re-run the model, while assuming that popular content is cached on the edge, results on the OPEX comparison for the likely and the premium scenarios for the baseline and caching scenarios are presented in Figure 5-4. A quick comparison between the OPEX of the solution with and without caching, shows that the OPEX with caching is approximately one third of the one without caching. This comparison shows an increase in the CAPEX costs in the case of using the cache due to the cost of the MEC infrastructure, but a much larger decrease in OPEX for the satellite backhaul. As a conclusion, the use of caching popular content on the edge with the assumed rate of 64% as explained previously, proves a reduction of 54.3% to 60.5% in OPEX costs, resulting in an important decrease (47 to 57 %) in terms of ACPU. A comparison between the obtained ACPU for the premium, likely and low-end scenarios for both cases with and without caching is recapitalized in Table 5-1.
From the table above, we can extract several conclusions:

- The ACPU reduction rate resulting from the use of the caching technology is almost halving (for the premium scenario).
- The ACPU reduction rate increases when the bitrate required per site increases, this is explained by the fact that the bigger data rates we offer, the more requests are served from the cached data.
- The ACPU for the low-end and likely scenarios without caching is economically viable (compared to the WTP discussed previously). Yet the ACPU for these scenarios with the use of caching concept is very cheap. Still, one needs to take into account the conversion of ACPU to actual ARPU (prices), using profit margins for the telecom operator and service providers.
- Caching technology is not viable with low throughput per user in remote areas (lower than 200 kbps).
- The deployment of the solution without using the caching concept is not cost-effective in the case of the premium scenario.
- A good speed thus a good QoE (Quality of Experience) can be offered to the inhabitants of rural areas thanks to the satellite-5G solution, in case caching techniques are deployed in the edge besides a policy solution as state aid or funding.

These results can give insights to the network operators on the deployment and pricing strategies that they can follow. For example, it might be that operators would start as a first step with a modest bitrate per user in order
to provide the universal broadband connectivity to these unserved areas (white areas) in the EU. The ACPU generated in this case is around 6.7 euro, yet the willingness to pay off the end user is 19 euro, so operators have a good margin to define their pricing strategy. By choosing the right margin of profit, operators can move forward smoothly to the premium scenario. In this way, they can cross-subsidize the offer of high-speed broadband by their first offer, which is the basic broadband service. On the other hand, the combination of the mobile and the satellite networks could be eligible to receive public funding according the EC criteria presented previously, as satellite networks were somehow marginalized from receiving public funding.

5.5 Sensitivity analysis

Besides the bitrate per user, which was already varied in the low-end/likely/premium scenarios, there are two important factors also affecting the required bitrate per site, which are the number of users and the caching rate. Therefore, we study these two parameters in more detail by running a sensitivity analysis for the model.

The input variables used in the sensitivity analysis are described in Table 5-2 below. Note that for this sensitivity analysis, we ran the cost model for the range in input variables as described in the table.

<table>
<thead>
<tr>
<th>Input variable</th>
<th>Distribution</th>
<th>range</th>
<th>Simulated scenario</th>
<th>Related formula in the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density: number of users</td>
<td>Uniform</td>
<td>13-400 inhabitants/km^2</td>
<td>Low-end</td>
<td>Equation 5-1</td>
</tr>
<tr>
<td>Caching rate</td>
<td>Uniform</td>
<td>0%-90%</td>
<td>Premium</td>
<td>Equation 5-13</td>
</tr>
</tbody>
</table>

5.5.1 Impact of the population density

In this section, we study the variation of the ACPU with and without caching data on the edge for the likely scenario (as an output) according to the variation of the population density per km^2 (as an input). Results of this simulation are presented in Figure 5-5.
Based on the European criteria of the classification of regions (Eurostat, 2018), we classified three main regions based on the population density. Rural areas are presented by the blue rectangle (density under 100 inhabitants per km²), sub-urban areas by the yellow rectangle (density between 100 and 300 inhabitants per km²) and urban areas by the orange rectangle (density over 300 inhabitants per km²). Several deductions can be extracted from the results of this simulation:

- A significant drop of the ACPU is seen in rural areas compared to a slight decrease in sub-urban and urban areas. This is due to the non-need of adding new base stations within a specific margin of population density. For example, moving from the density of 13 inhabitants per km² to 26 does not require the installation of new base station which means the same cost of the infrastructure will be divided by the double number of users.
- A saturation point is reached starting from the population density of 200 inhabitants per km². This is because increasing the number of users extensively induces the increase of the required data rate per site thus increasing the number of base stations and satellite terminals that should be installed.
- Transition points between different densities with high ACPU can be observed in Figure 5-5, indicated with red circles. This high ACPU is due to the need to deploy new base stations to satisfy the additional bandwidth requirement, yet the number of users are not enough to cover this additional cost (the cost of the new installed base station).

Similar to other broadband solutions, the cost per user of deploying the satellite-5G solution in urban areas is much cheaper than in rural areas.
The low cost of the proposed solution in sub-urban and urban areas can give insights to the operators about the suitable use of a similar solution to improve their services at a low cost. Two use cases for both the sub-urban and urban areas might be of interest.

The first use case for sub-urban areas consists on the consolidation of the “poor” terrestrial connection with the satellite connection to improve the speed and thus the QoE. This use case is addressed in chapter 7.

The second use case concerns the use of the satellite solution in urban areas. This use case involves the delivery and offload of content (multimedia, network software updates etc.) in the mobile network via satellite alone or a combination of satellite and terrestrial links for local caching. This use case is addressed in chapter 6.

5.5.2 Impact of the caching rate

We argued previously the assumption on the caching rate in section 5.4.6.1. However, this assumption has a big impact on the results, as can be seen from the mathematical formulation of the model (section 5.4.2). To this end, we study in this section the variation of the CAPEX and OPEX in function of the caching rate. Results of this simulation in presented in the figure below:

![Variation of CAPEX and OPEX according to the caching rate](image)

*Figure 5-6: Variation of the CAPEX and OPEX for the premium scenario in function of the variation of the caching rate*

Several interpretations can be extracted from the Figure 5-6 related to CAPEX and OPEX. On the one hand, the CAPEX increases with the use of caching due to the cost of the MEC deployment, this can be observed in the figure above at the 10% caching rate point. On the other hand, the CAPEX decreases slightly (can be seen starting from point 20%) with the increase of the caching rate due to the decrease of the traffic that needs to be sent via satellite, thus the decrease of the number of satellite terminals needed to handle the traffic. On the operational costs side (OPEX), there is a significant decrease in function of the caching rate increase. The more data is cached, the less traffic is sent via the satellite link, thus the less the satellite capacity cost is paid. One could think, based on these results, to use a high rate of caching to decrease the operational costs, however an in-depth analysis of the consumer traffic and forecasting and optimization algorithms for popular content are needed to determine the reasonable range of the caching rate as elaborated in [47].

To conclude, the main observations from the impact of varying the key inputs of the model on the outcomes are summarized in Table 5-3 below.
Table 5.3 Main observations of the variation of the key parameters of the cost model.

<table>
<thead>
<tr>
<th>Input variable</th>
<th>ACPU</th>
<th>CAPEX</th>
<th>OPEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density: number of users</td>
<td>The ACPU is very sensitive to the population density variation hence to the number of users and it is very low in dense urban areas.</td>
<td>The CAPEX increases with the increase of the number of users because new sites needs to be deployed to cover the need of the new users.</td>
<td>The OPEX increases with the increase of number of users because of the increase of the total bitrate required for the new users.</td>
</tr>
<tr>
<td>Caching rate</td>
<td>The ACPU decreases significantly due to the decrease of the OPEX while increasing the caching rate.</td>
<td>Slightly affected by the variation of caching rate.</td>
<td>Significantly affected by the variation of the caching rate because we save on the satellite capacity costs when we cache more data on the edge.</td>
</tr>
</tbody>
</table>

5.6 Discussion: “putting this into context”

To validate our results, we compare them to the findings in [49]. In this publication, in order to cover rural areas in Greece with a population density of 33 inhabitants per km$^2$, the required ARPU for the FTTdp solution is 332 euro. To make a fair comparison, we will compare our generated ARPU for the premium scenario (i.e. a data rate of 30 Mbps) for the same population density. The generated ARPU for the Satellite-5G is only 74 euro, considering the average margin profit of 11% on top of the ACPU [36]. We can hence prove that the combination of backhaul satellite and fronthaul 5G networks is more cost effective than the FTTdp technology.

Moreover, a quick back of the envelope calculation of the fiber-5G solution presented previously in the introduction section, shows that the CAPEX to deploy such a solution are more than 5M euro, which results in an ACPU of 67.7 euro per month for a timeframe of 5 years, this without counting OPEX. Hence, the combination of the fiber and 5G mobile networks is not (yet) the right broadband solution to cover rural areas (a table summarizing this back of the envelope calculation is drafted in the Appendix 0).

On the other hand, the price of the satellite-only broadband solution presented in [50] is 99 euro for 10 to 20 Mbps as a download speed for a total of 2 GB data per month. Making the extrapolation, this would result in a price of almost 200 euro per month for providing 30 Mbps. In addition, we have to count the cost of the satellite terminal that the end user has to buy as well as its installation and maintenance costs. Hence, the total price per month is also more expensive than the 5G-satellite solution, even if considering the baseline scenario without caching.

The ACPU of the likely scenario could motivate operators to offer more speed to the end user while bearing in mind that offering broadband connectivity in rural areas will eventually lead to the adoption of different services, e.g. tech-agriculture, farm business, e-services, etc. In turn, this may lead to new sources of revenues for the operators, which could make the use case more cost-effective than providing only the universal Internet service. Offering diverse services could be more profitable with the deployment of network slicing within the upcoming 5G networks due to the virtualization of network functions (Han et al., 2017).

However, the price itself is not the only contributing factor as explained previously in the introduction. Hence, operators in rural areas should look at the specific demand by the targeted users (e.g. new services targeted to their life).
The date consumption figures have assumed Western European data volumes. It is therefore worthwhile considering the affordability of this in this context. Consider the following set of parameters:

- Per scenario 2b, 1050 end users per satellite backhauled “base station”;
- A single operator with 15,000 base stations and 8M end users;
- Using satellite backhauls to increase geographic coverage to enable access to additional 5G spectrum;
- No caching implemented.

This means each satellite backhaul base station a contribution between €9.45k and €30.45k. If these costs are shared across the whole network as a means to access the additional spectrum the net contribution per end user will be low. This is shown in the following figure:

![Figure 5-7: Average ARPU contribution needed to support a number of satellite BS](image)

From this, it is clear that, depending on how aggressive or conservative the data consumption levels are, that for between about 50 and 200 satellite sites has negligible impact on the average costs per end user.

5.7 Network slicing: cost allocation model

The considered scenario counts 1050 users to be served with two services (eMBB VoIP and eMBB video). The chain of network functions for the data plane and the required throughput per user for each service is based on input from literature, as well as the percentage of the traffic per service and the total generated traffic per service are presented in the table below:

<table>
<thead>
<tr>
<th>Slice</th>
<th>Chain of VNFS</th>
<th>throughput Per user</th>
<th>% traffic</th>
<th>Total traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>VoIP</td>
<td>NAT-FW-TM-FW-NAT</td>
<td>64kbps</td>
<td>20%</td>
<td>13.44 Mbps</td>
</tr>
<tr>
<td>Video</td>
<td>NAT-FW-TM-VOC-IDPS</td>
<td>4 Mbps</td>
<td>80%</td>
<td>1.68 Gbps</td>
</tr>
</tbody>
</table>
For the data plane network functions, we apply the three approaches described in section 4.2.1.3 and we compare their results to the findings in literature. Results of the model are presented in Table 5-5. The first column presents the required CPU cores for the different virtualized middleboxes based on the number of concurrent operations. The number of concurrent operations that each function needs to handle is derived by linking the original findings in [29] with the carried traffic in terms of Mbps. Results generated based on the second approach use the processing requirement per user considering the carried traffic as well. Yet, results of the third approach are driven using the CPU-core-to-throughput relationship. The comparison of those different findings to those in literature [25]-[30] allows to conclude that the number of required CPU based on the throughput-to-CPU relationship seems to be the more realistic one.

Table 5-5 Hardware requirements per VNFs per service for the three approaches

<table>
<thead>
<tr>
<th></th>
<th>Number of CPU cores approach 1</th>
<th>Number of CPU cores approach 2</th>
<th>Number of CPU cores from approach 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAT</td>
<td>0.35</td>
<td>0.966≈=1</td>
<td>1</td>
</tr>
<tr>
<td>FW</td>
<td>0.7</td>
<td>0.945≈=1</td>
<td>1</td>
</tr>
<tr>
<td>TM</td>
<td>0.35</td>
<td>13.965=14</td>
<td>2</td>
</tr>
<tr>
<td>VOC</td>
<td>0.7</td>
<td>5.67=6</td>
<td>1</td>
</tr>
<tr>
<td>WOC</td>
<td>0.35</td>
<td>5.67=6</td>
<td>1</td>
</tr>
<tr>
<td>IDPS</td>
<td>0.7</td>
<td>11.235=12</td>
<td>2</td>
</tr>
</tbody>
</table>

Adopting the CPU-core-to-throughput approach, the hardware requirements for both eMBB voice and video slices are summarized in the table below:

Table 5-6 Hardware requirements of the data plane network functions for eMBB voice and video slices

<table>
<thead>
<tr>
<th>VNF\Service</th>
<th>Voice, throughput=13.44 Mbps</th>
<th>Video, throughput =1.68 Gbps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CPU</td>
<td>RAM: GB</td>
</tr>
<tr>
<td>NAT</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>FW</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>TM</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>VOC</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>WOC</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IDPS</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
For the control plane network functions, we apply the proposed model described in section 4.2.1.1, assuming a user inactivity of 10 seconds, the mobility model adopted in [6] and 1050 users. In addition, based on the 3GPP view on network slicing, several NFs of the control plane are shared between slices. These common network functions are the AMF, NRF, NEF, UDM, AUSF and NSSF [51], [52]. Those functions are represented with grey columns in Table 5-7. Moreover, since the video slice is carried over satellite link, we need to deploy a satellite multicast function and a Nano CDN node next to the edge for popular video’s caching purpose.

Results of the model for the two slices being eMBB voice and video are recapitulated in the following table:

<table>
<thead>
<tr>
<th>Technical requirement</th>
<th>UPF</th>
<th>AF</th>
<th>AMF</th>
<th>SMF</th>
<th>PCF</th>
<th>NRF</th>
<th>NEF</th>
<th>UDM</th>
<th>AUSF</th>
<th>NSSF</th>
<th>Sat-multicast NF</th>
<th>AF (Nano CDN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>eMBB voice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Memory</td>
<td>9</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HDD</td>
<td>12</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>10</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>eMBB video</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>8</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Memory</td>
<td>13</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HDD</td>
<td>28</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

It is clear from results presented in Table 5-7 that, like the RAN, video slices require more core network resources than voice slices.

5.7.1 Resource allocation for video and voice slices

Given the hardware requirements of both voice and video slices presented in the previous section, we apply the proposed allocation model. The model is based on the preconfigured VMs (presented in Table 5-8 and described in section 4.2). The results of the required VM types for each slice as well as for the shared network functions are presented in the following table:

<table>
<thead>
<tr>
<th>VM type</th>
<th>S-VM</th>
<th>M-VM</th>
<th>L-VM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shared Nfs</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Video slice</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Voice slice</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Similar to [13] and [53], we consider a Blade server because of its capability to provide more processing power in less space, which allows to simplify cabling and storage. The Blade server consists of 8CPU, 64 GB RAM, 1000 GB HDD and 4 Ethernet cards of 10 Gbps each. Moreover, for the reliability of the network, we consider a redundant VM for each NF. Hence, within the preconfigured VM option, we need 10 servers to satisfy the required hardware requirements of the two slices. Orthogonally, within the configurable VM option discussed in section 4.2, we need only 8 servers from the same server type.
On the other hand, for the SMF, we said previously in section 4.2.1 that it needs a good networking interface. Thus, to investigate if we have a limitation in terms of networking interface for the Blade servers reserved based on the CPU metric, we calculate the generated traffic per user for SMF and for AMF as well. We assume that the average packet size is 250 bytes for the control messages generated by SMF and AMF (similar to the assumption of [54] for the vMME). The calculation results in 18.418 and 14.626 bits per second per user for the SMF and AMF respectively. Hence, for our scenario with 1050 users, the AMF requires 15.4 kbps to be reserved on the network interface, the SMF requires 38.8 kbps (for both video and voice slices). Therefore, if we allocate 1Gbps on the network interface card NIC for each VNF, it is more than enough. Hence, we do not have a limitation on the networking interface resources.

5.7.2 Cost allocation for video and voice slices

The cost of the network infrastructure installed to serve the remote two villages with eMBB voice and video services was presented in section 5.4. These cost figures are used in addition to other inputs (detailed in the table below) as inputs for the cost allocation model.

Table 5-9 Cost inputs for the cost allocation model

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>latency eMBB video in ms</td>
<td>300</td>
<td>latency: Packet Delay Budget from &quot;3GPP standard QoS class identifiers&quot; for Non-Conversational Video (Buffered Streaming) [23]</td>
</tr>
<tr>
<td>latency eMBB voice in ms</td>
<td>100</td>
<td>latency: Packet Delay Budget from &quot;3GPP standard QoS class identifiers&quot; for Conversational Voice [23]</td>
</tr>
<tr>
<td>Throughput eMBB video (in Mbps)</td>
<td>4</td>
<td>Assumption</td>
</tr>
<tr>
<td>Throughput eMBB voice (in Mbps)</td>
<td>0.64</td>
<td>Assumption</td>
</tr>
<tr>
<td>Weighting Coefficient</td>
<td>0.3</td>
<td>Assumption</td>
</tr>
<tr>
<td>Qco Video</td>
<td>0.718</td>
<td>Calculated based on Equation 4-3</td>
</tr>
<tr>
<td>Qco Voice</td>
<td>0.282</td>
<td>Calculated based on Equation 4-3</td>
</tr>
<tr>
<td>CPU cost driver: video</td>
<td>0.59</td>
<td>Calculated using the model</td>
</tr>
<tr>
<td>CPU cost driver: voice</td>
<td>0.41</td>
<td>Calculated using the model</td>
</tr>
</tbody>
</table>

Considering these input values, we run our model to allocate the cost of the network to the two slices being eMBB video and eMBB voice. Results of the model are represented in the following diagram (Figure 5-8):
Several interpretations can be extracted from Figure 5-8. First, the eMBB video slice bears the more significant amount of the network costs (68% compared to only 32% for the voice slice). This is reasonable, because it requires more throughput than the voice slice on both RAN and backhaul, as well as more computing resources on the core network part. However, the cost of the throughput of the voice slice is still important, which can be justified with the fact that not only the required throughput is counted in the cost allocation algorithm but also the latency (Equation 4-3), as voice is prioritized on the RAN and the backhaul parts. This prioritization is also translated into cost.

5.7.3 Cost saving resulting from the use of network slicing in the core network
NFV and network slicing paradigms promise to reduce the network costs and allow for more cost-efficient deployments. In this section, we investigate these promises. Given the dimensioning model for network slicing, we know the exact amount of resources that each slice requires. Furthermore, we count redundant resources for reliability purposes. Hence, we can deduce how much resources the core network has to provide to fulfil the slice needs. Afterwards, calculating the cost of the core network resources and comparing it to the cost of the traditional core network (without NFV deployment) allows to calculate the cost saving of the use of virtualization technology. In the appendix 11.7, we detail the cost inputs used to derive the cost of the virtualized 5G core network. We have two figures of the traditional core network cost, one quoted in term of number of users and one in terms of traffic (i.e. Mbps). Therefore, we calculate the cost of the core network and we quote it also per user and per Mbps.

The result of the comparison between the core network cost with NFV deployment versus without, is summarized in Table 5-10. Given these results, the cost saving due to the use of virtualization on the core network is 45% if the cost is quoted in Mbps, yet, it is only 12% if the cost is calculated per user comparing to the sources mentioned below in Table 5-10. Hence, we prove that the use of NFV and network slicing reduce the cost of the core network deployment.
Table 5-10 Cost reduction resulting from the use of NFV in the core network

<table>
<thead>
<tr>
<th></th>
<th>Cost virtualized 5G core</th>
<th>Cost of the traditional core network</th>
<th>Cost reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost 5G core per Mbps</td>
<td>21€</td>
<td>38 euro per Mbps (5 to 6 euro per Mbps for the hardware and 30 to 35 euro per Mbps for software) (Table 11-6)</td>
<td>45%</td>
</tr>
<tr>
<td>Cost 5G core per user</td>
<td>53€</td>
<td>60 euro per user [11]</td>
<td>12%</td>
</tr>
</tbody>
</table>

5.8 Recommendations and future work

The main takeaways and recommendations from the business modelling of this use case are:

- The proposed satellite-5G solution is economically viable without caching for a modest bitrate per user and with caching for a good bitrate per user (when comparing to the WTP of the end user);
- Caching popular content to the edge saves from 40% to more than 50% of the OPEX depending on the provided bitrate per user and the caching rate used;
- Installing caching technology is not useful when a low throughput per user in rural areas is expected (lower than 200 kbps);
- The ACPU is very sensitive to the population density variation (i.e. to the number of users);
- The CAPEX is only slightly affected by the variation of caching rate, however the OPEX is very sensitive the caching rate.

An interesting future work item would be a detailed sensitivity review for different regions where data consumption expectations and WTP vary significantly from the Western European data used in the previous sections.

These results could motivate operators to offer good speed to the end user while bearing in mind that offering broadband connectivity in rural areas will eventually lead to the adoption of different services, e.g. tech-agriculture, farm business, e-services, etc. In turn, this may lead to new sources of revenues for the operators, which could make the use case more cost-effective than providing only the universal Internet service. In addition, using new technologies such as caching techniques and network slicing could results in a significant cost reduction.
6 Use case 1: Edge delivery & content offload

6.1 Introduction

This use case aims at providing efficient multicast/broadcast delivery to network edges for content such as live broadcasts, ad-hoc broadcast/multicast streams, group communications, and MEC VNF update distributions. It involves the delivery and offload of content (multimedia, network software updates etc.) in the mobile network via satellite alone or via a combination of satellite and terrestrial links for local caching. Onward delivery is by fetching from the cache and has the advantage of lower latency and potential improved QoE.

The scenarios associated with this SaT5G use case correspond to satellite broadcast/multicast functions and the use of caching. This can be implemented via a standalone fixed terminal or via delivery to the mobile edge cache for onward delivery to UEs within the MNO’s 5G network.

Adding broadcast/multicast resources in the network to be able to deliver the most popular on demand as well as live content towards the edge nodes of the network enables to offload a significant part of the traffic and/or to optimise the network infrastructure dimensioning (especially the backhaul links) in the lower density populated areas, where the cost per user is the highest [1].

The selected scenario consists of a combination of updating the VOD content of CDN nodes with providing live streaming. These services are delivered to all subscribers of an operator through its 5G network. Storage and streaming capacities are available at the level of a node that covers several base stations. The local caches in these nodes are provisioned with popular live and VOD content in multicast. The nodes are also equipped with a multicast to unicast agent capable of transforming multicast live feeds into unicast live content that can be streamed on 5G networks. The main difference between this use case and the previous one (use case 2), in term of using caching techniques, is that within this use case the satellite backhaul is used to update the content of the caching nodes, yet in the previous case the satellite backhaul is used to provide the non-cached content.

For this scenario, the techno-economic analysis aims to realize several objectives:

- Evaluate the Total Cost of Ownership (TCO) of the proposed solution (section 2.2);
- Derive the Average Cost Per User (ACPU) for the satellite multicast using the TCO cost model;
- Quantify the use of multicast satellite link over the terrestrial link for offloading video content, by quantifying the gained bandwidth on the terrestrial link;
- Study the best placement of the CDN nodes in the network topology based on the trade-off between cost vs bandwidth savings.

6.2 Network architecture

The proposed solution proposed within the SaT5G project to update the CDN nodes content to the selected scenario, is composed of:

1. A 5G core network that treats and processes the offered services;
2. A satellite gateway connected to the 5G core network and to the terrestrial backhaul network at an adjustable placement according to the trade-off between the cost vs bandwidth savings via a fiber connection, which is responsible for forwarding the traffic from the core network to the CDN nodes via a satellite link;
3. A satellite terminal installed near the CDN nodes that receives the traffic from the satellite gateway via the satellite link and sends it to the CDN nodes;
4. Finally, a CDN node that hosts the VOD and Live content.

The network architecture is presented as follows:

![Network architecture for updating CDN content](image)

**Figure 6-1: Network architecture for updating CDN content**

### 6.3 Qualitative business modelling

Based on the possible business models described in section 2.1 and in section 3.3, the most likely scenario for this case is the 1-F-B in a short-term period or the 1-D-B in the mid to long term. The satellite capacity needed for this scenario has a different pattern between day and night, since during the day only the live service is running but during the night both VOD updating and lower levels of live services need the satellite link to fulfil their needs in term of throughput. The VOD content especially can require some high boosts in required throughput. In the static capacity reservation business model, the MNO has to reserve the sum of the two throughputs required by the two services even if they are not fully used the entire time. This may lead to more cost paid for the satellite capacity by the MNO and an inefficient resource allocation from the SNO perspective. Therefore, the suitable business model in the medium to long term reservation is the 1-D-B, which means the MNO asks the broker to reserve a dynamic satellite capacity according to his need. The broker in this case take the role of a re-seller as explained in section 3.3.3.

### 6.4 Quantitative business case evaluation: TCO model

As described in chapter 2, we use a TCO model to evaluate the economic viability of the proposed solution for the selected scenario.

#### 6.4.1 Cost model structure

The main inputs of the model are the bill of materials (BOM), the number of users, the bitrate needed for live streaming and VOD updating, the video subscription rate and the time horizon of the project. Those inputs feed
into a cost model that consists of three sub-models in alignment with the network architecture components presented in the section 2.2.1. The first sub-model is designed for the edge. It incorporates the CAPEX of the CDN node or MEC, the CAPEX of the satellite terminal, and the common CAPEX and the OPEX of all edge components. The second one models the satellite network; both CAPEX and OPEX are considered. The third and last one englobes all overhead costs. After the calculation of the CAPEX and OPEX for all these blocks, the TCO can be derived. Hence, given the TCO as well as number of users, the ACPU can be derived as an output of the model.

6.4.2 Mathematical formulation of the model
In the previous section, the structure of the proposed cost model has been presented, from a high-level perspective. In this section, we will detail formulas used to calculate both CAPEX and OPEX for each sub-model. An overview of abbreviations can be found in Table 11-1.

Cost of the edge:
The cost of the edge incorporates the CAPEX of the CDN node, the CAPEX of the satellite terminal, the common CAPEX and the OPEX of all the edge components. The number of equipment needed depends on the dimensioning process of the site, which in turn depends on the bitrate to be provided to the site. The bitrate per site consists of the bitrate needed for the live service (Equation 6-1) and the one needed for VOD content updating (Equation 6-2):

Bitrate requirement:
The contribution link concerns the 5 most popular channels (presented with their different layers in Table 11-2).

\[ \text{Equation 6-1 Bitrate}_{\text{Live}} = N_{\text{channels}} \times \sum_{i=1}^{5} \text{Layer}(i)_{\text{speed}} \]

In order to derive the needed bitrate to update the VOD content, we first need to calculate the local storage required to host this content. The storage requirements hence are:

\[ \text{Equation 6-2 Storage}_{\text{VOD}}(\text{MB}) = VODcat_{\text{size}}(h) \times N_{\text{sec}}_{\text{inhr}} \times \sum_{i=1}^{5} \text{Layer}(i)_{\text{speed}} \]

Hence, the bitrate required to update this content is determined using the following equation:

\[ \text{Equation 6-3 Bitrate}_{\text{VOD}} = \text{Storage}_{\text{VOD}}(\text{MB}) \times \text{Updating}_{\text{rate}}/(N_{\text{updatehr}} \times N_{\text{sec}}_{\text{inhr}}) \]

Therefore, the total bitrate needed to serve one CDN node is the sum of these two bitrates\(^7\):

\[ \text{Equation 6-4 Bitrate}_{\text{CDN}} = \text{Bitrate}_{\text{Live}} + \text{Bitrate}_{\text{VOD}} \]

CAPEX and OPEX of the edge:
The CAPEX and OPEX of the CDN nodes are determined using the following formulas

\[ \text{Equation 6-5 Cost}_{\text{CDN}} = \text{CAPEX}_{\text{CDN}} + \text{OPEX}_{\text{CDN}} \]

\[ \text{Equation 6-6 CAPEX}_{\text{CDN}} = N_{s} \times C_{s} + N_{stg} \times C_{stg} + \frac{Mes_{\text{mag}}}{N} + C_{\text{inst}} \]

\[ \text{Equation 6-7 OPEX}_{\text{CDN}} = CDN_{\text{PwrConsmp}} \times C_{\text{watt}} + M \]

\(^7\) The total required bitrate could be more optimized since the bitrate for VOD catalogue updating is required only during night, but since we are using satellite multicast, it will not have a big effect on the ACPU.
The total CAPEX of all CDN nodes is the CAPEX per node multiplied by the number of nodes. The number of satellite terminal needed to serve the CDN node is derived by Equation 6-8.

\[ \text{Equation 6-8} \quad NB_{ST} = \frac{\text{Bitrate}_{CDN}}{\text{STcapacity}} \]

Hence the CAPEX of the satellite terminal is:

\[ \text{Equation 6-9} \quad CAPEX_{ST} = NB_{ST} \times \text{Cost}_{ST} + \text{C}_{\text{Inst}} \]

Therefore, the cost of the edge is:

\[ \text{Equation 6-10} \quad CAPEX_{edge} = CAPEX_{ST} + CAPEX_{CDN} \]

**Cost of the satellite network:**

The cost of the satellite capacity cost and the satellite OPEX are calculated using the following formula:

\[ \text{Equation 6-11} \quad C_{\text{satCaps}} = \text{Bitrate}_{CDN} \times 12 \times C_{\text{satMbps}} \]

\[ \text{Equation 6-12} \quad \text{OpeX}_{\text{sat}} = C_{\text{satCaps}} + P_{\text{satGat}} \times C_{\text{watt}} + M \]

In addition, the total CAPEX, OPEX and TCO as well as the additional costs are calculating using the same formulas described in the Use case 2 chapter.

### 6.4.3 Model inputs

Inputs used to run the cost model are presented in the tables in Appendix section 11.1.

In addition, the cost model is based on several assumptions that should be made to have as realistic results as possible:

- The local cache is provisioned with 60 hours of content that covers 80% of popular content requested by end users;
- The remaining requested content (20%) will be streamed directly in unicast, using the existing terrestrial links;
- We need only to update 30% of the local VOD catalogue every night as content stays popular during 3 days on average;
- The update process is done during night, spread over 8 hours;
- We assume a terrestrial operator (MNO) that has installed (or will install) 5G infrastructure and is looking for optimizing the use of the backbone network. We assume the MNO itself has the rights for the content or an agreement in place with content owner to use processes/systems to distribute their content efficiently.

### 6.4.4 Simulation and results

The potential scenarios that can be investigated within this specific use case are driven by the condition of the terrestrial backbone and backhaul networks since the satellite multicast will be used to save bandwidth on the “poor” links within the network. Starting from there, we define two distinct scenarios to be studied: (i) the case of a Western European country and (ii) a case of a Sub-Saharan African country. To understand the difference between the two scenarios, we use the following network structure as a reference network topology (Figure 6-2):
The first case corresponds to a Western European country where, generally, the network backbone is fibre which is almost deployed up to exchange nodes, so the satellite can be used in few remote and rural areas where the link between the tier 1 and exchanges is not yet fiberized. However, for case of the Sub-Saharan African countries where according to the World Bank report [56], the fibre backbone is still in its early stage: the fibre-based backbone network covers only 33% to 54% of the population in sub-Saharan Africa (e.g. case of Botswana, Nigeria...) [57].

For the two scenarios, we can categorise the country under study in to five main regions:

1) Areas where FTTH is deployed, generally in dense urban and some of the urban areas;
2) Areas where FTTH is not yet deployed but where fiber is deployed up the exchanges or to the cabinet;
3) Areas where fiber is installed up to the Tier 1 level but where the link between Tier 1 and exchanges is of bad quality and cannot support VOD or live streaming services;
4) Areas where a backbone exists, but where fiber is installed only up to the metro level and the rest is copper (e.g. rural areas);
5) Areas where there is no backhaul network installed (the most remote areas).

The first two categories are not relevant in this use case. The fifth category is relevant but is already studied in use case 2 (chapter 5). Hence, only in the third and fourth categories, this use case makes sense.

The overall operator network consists of a mix of the aforementioned categories, and each category represents a percentage of this network. This percentage is used to derive at which level of the network topology the CDN nodes should be installed and how many. The main difference between the two scenarios suggested to be studied is in these percentages, e.g. the percentage of the FTTH (first category) in France is higher than the percentage of FTTH coverage in Botswana for example.

Let us denote the percentage of the first category as A%, second as B%, third as C%, fourth as D% and the last one as E%; the sum of all of them is 100%. These percentages are varied in the simulation in order to derive for each scenario the required amount of CDN nodes that need to be installed.
Scenario of Western European countries: France as an example

In this scenario, we take the case of France. In the baseline scenario, the CDN nodes will be installed at the same placement in the network (i.e. same position in the network topology). It is like assuming that we have the same network status in all the country. In France, for example, Orange has 21 million customers [58] and based on the generic network topology presented in Figure 6-2, we need 20 nodes if CDN nodes will be installed at the core level, 100 nodes at the metro level, 1000 at the tier1 level and 6000 at the exchange level. A second scenario (further referred to as likely scenario), considers the status of the entire network of the country under study (France in this case). Hence, we have to install CDN nodes next to exchanges in some areas, and next to tier1 nodes in other areas (and this according to the five region types discussed above).

Scenario of Sub-Saharan African countries: Botswana as an example

In this scenario, we study the case of Botswana. Again, the model will be run for two scenarios: the baseline (CDN nodes at the same network topology level) and the likely scenario (different placement of the CDN nodes within the network based on the five region types are taken into account).

For the first scenario, we need to rescale the number of nodes to match the geography of Botswana (only 589,909 households [59] spread out over a surface of 600,370 km², which is 3 times the surface of the UK). So, for the first iteration of this scenario, we will scale these numbers based on the number of premises but based also on the served areas (since we need more nodes to serve the sparse households’ clusters). Therefore, we need to install 3 nodes at the core level, 9 CDN nodes at the metro level, 75 nodes at the tier1 level and 426 nodes at the exchange level.

In both scenarios, if the CDN nodes are installed next to the exchanges, we have to consider an extra cost of small cabinets to host the CDN nodes since the space in the exchange nodes is not sufficient to host the CDN equipment.

6.4.5 Results of business case analysis for the baseline scenario

The baseline scenario is the simulation of the model for both scenarios of France and Botswana with the assumption that we install all CDN nodes at the same position in the network (as described previously), though this position will be varied to find the trade-off between the ACPU and the saved bandwidth on the terrestrial link. We applied the cost model described previously using the inputs of both countries as detailed in the model input section.

The results for the both scenarios (e.g. case of France and Botswana) of the Total Cost of Ownership (TCO) of the proposed solution as well as the total bandwidth saving in function of the number of CDN nodes installed are presented in the following figures:
The resulting ACPU in function of the number of nodes is recapitulated in the tables below:

**Table 6-1: ACPU of the France case for the different location possibilities of installing the CDN nodes**

<table>
<thead>
<tr>
<th>ACPU</th>
<th>#CDN</th>
<th>20</th>
<th>100</th>
<th>1000</th>
<th>6000</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACPU</td>
<td>0.0016€</td>
<td>0.006 €</td>
<td>0.057 €</td>
<td>0.355 €</td>
<td></td>
</tr>
</tbody>
</table>

**Table 6-2: ACPU of the Botswana case for the different location possibilities of installing the CDN nodes**

<table>
<thead>
<tr>
<th>ACPU</th>
<th>#CDN</th>
<th>3</th>
<th>9</th>
<th>75</th>
<th>426</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACPU</td>
<td>0.023€</td>
<td>0.038€</td>
<td>0.20€</td>
<td>1.082€</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6-3: The TCO and the bandwidth saving for the case of France**

**Figure 6-4: The TCO and the bandwidth saving for the case of Botswana**

**Figure 6-5: OPEX reduction resulting for the satellite multicast**
The main takeaways from these findings are:

- Using satellite multicast decreases the OPEX for the integrated SaT5G solution (Figure 6-5).
- The ACPU is higher in low population density areas than in high population density areas (e.g. France vs Botswana), since we need to install more nodes to cover the sparse households’ clusters while having a smaller number of users.
- The total bandwidth saving increases with the increase of the number of CDN nodes installed because we save more traffic on the “poor” links with installing more nodes.

6.4.6 Results of business case analysis for the likely scenario

As described in section 6.4.4, the likely scenario consists of a mix of different region types, hence, we have to consider the percentage of each region from the overall network in order to calculate the required number of nodes to be installed.

**Case of France:**

According to [60], 10.1% of French people do not have access to a fixed connection of quality between 3 and 4 Mbps and 34.31% of French citizens do not have access to high speed broadband of 30Mbps (automatically 34.31% don’t have access to FTTH). This implies, in term of percentages discussed in the section 6.4.4, that:

- \((A+B)\% = 65\%\);
- \((C+D+E)\% = 35\%\).
- We can assume that \(D\% = 10\%\) (from the fact that 10.1% of French don’t have access to a fixed connection of quality between 3 and 4 Mbps).
- \(C+E = 25\%\); if we assume that white areas in France is a small fraction, we can then assume that \(E\) is from 1 to 5%, hence \(C\) is from 24 to 20%

We only count here \(C\) and \(D\) as the others are not relevant to the use case.

![Figure 6-6: Network status in France in terms of existing backbone](image)

**Case of Botswana:**

The numbers we have for the case of Botswana, presented in [61], discuss the percentage of the population that live within a range of numbers of kilometers of an active fiber node. The number of people within reach of a
broadband service provided by fiber depends on the range of the fixed or wireless broadband access network used from the fiber node and onwards. This study that 65.1% of the population lived within a 50km range of an operational fiber-optic network node, 44% of the population lived within a 25km range and 22.3% of the population lived within a 10km range of an operational fiber network node.

From these results we can deduce the following:

- (A+B) % = 22.3% => (C+D+E) % = 77.7%
- We can assume that D% = 100% - 65.1% = 34.9% (from the fact that 65.1% of the population lived within a 50km range of an operational fiber-optic network node.)
- C + E = 77.7% - 34.9% = 42.8%; if we assume that white areas in Botswana are between 5 to 15% (E) hence C is from 37.8% to 27.8%

![Botswana network status](image)

*Figure 6-7: Network status in Botswana in terms of existing backbone*

We run the model for both countries with the percentages described above and recapitulated in the table below is the number of CDN nodes needed, the ACPU and the total bandwidth savings:

**Table 6-3: The ACPU and bandwidth savings for both countries for the likely scenario**

<table>
<thead>
<tr>
<th>Country</th>
<th>ACPU</th>
<th>CDN</th>
<th>Saved bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>22%</td>
<td>10%</td>
<td>0.30€</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>108,157 Mbps</td>
</tr>
<tr>
<td></td>
<td>35%</td>
<td>55%</td>
<td>0.65%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13,405 Mbps</td>
</tr>
</tbody>
</table>

Table 6-3: shows that if we take the status of the entire network into consideration, we can reduce the number of CDN nodes required (in some regions, they need to be installed next to the exchanges (C%), in other next to Tier1 (D%) and for the rest of the network, it is not needed to install them). However, the number of users is also less because we consider only users concerned by the use of the CDN nodes to enhance their connectivity.
6.5 Sensitivity analysis
In the simulation and results section, we elaborated a basic sensitivity analysis on:

- Geographical region i.e. Western Europe versus Sub-Saharan Africa.
- Number of nodes based on the placement within the network topology
- Number of nodes based on the entire network status, dynamic placement (likely scenario) versus static placement (baseline scenario).

In the second iteration (during the extension period) more sensitivity analysis is expected and more specifically on the different region percentages used in the likely scenario.

6.6 Discussion: “putting this into context”
The aim of this use case is to study the affordability of the Sat-5G integrated solution to enhance the terrestrial network links uncapable to provide live streaming services and high capacity bursty traffic. Results have shown reasonable average cost per user and significant bandwidth savings. These results vary from one scenario to another given the status of the entire network and the number of users, but in all the studied scenarios the proposed solution is viable and can enhance the terrestrial network.

6.7 Recommendation and future work
Based on the studied scenarios the main takeaways are:

- Using satellite multicast decreases the OPEX for the integrated SaT5G solution which implies a decrease in the ACPU as well.
- The ACPU is higher in low population density areas than in high population density areas (e.g. France vs Botswana), since we need to install more nodes to cover the sparse households’ clusters while having a smaller number of users.
- The total bandwidth saving increases with the increase of the number of CDN nodes installed because we save more traffic on the “poor” links with installing more nodes.
- Taking the status of the entire network into account reduces the total number of CDN nodes required, hence reduces also the cost.

These results give insights into operators if they need to improve their network in some regions in order to provide video services such as VOD and live streaming and they do not want to upgrade their networks due to the important investment needed to realize this. As a future work, a cost comparison can be made to assess the cost savings resulting from deploying the Sat5G solution versus upgrading the terrestrial network (upgrading copper) or installing fiber network.

One related area of research could be to consider the embedded carbon costs of deploying satcoms widely. Recent articles are suggesting that the consumption of OTT video streaming content is adding significantly to our greenhouse gas emissions (such as [62] suggests around 300Mt emitted and 1% of the total).
7 Use case 3: 5G to premises

7.1 Introduction
This use case is mainly relevant to homes and small office home office (SOHO) premises located in underserved areas of developed countries, which are served with terrestrial telecommunication network infrastructure (xDSL or cellular access) of poor bandwidth performance (e.g., users are located far from the DSLAM or far from a cell tower). In such underserved areas of developed countries, the use of satellite to complement the existing terrestrial broadband access link can lead to a Hybrid Satellite/Terrestrial Multiplay Scenario which can be envisaged in order to benefit from the low latency of terrestrial networks and the high bandwidth of satellite networks. In particular, complementing the existing and performance-limited terrestrial broadband link (xDSL or Cellular access) by a satellite broadband link with multicast and caching capabilities is considered here.

This set of scenarios is particularly relevant if satellite can provide more bandwidth for premium clients, typically multi-screen and UHD, and if user experience for Internet applications is raised to a level similar than those of terrestrial networks (in terms of latency, throughput at peak hours for a large number of clients, etc.) [1].

The selected scenario to be investigated is scenario 3a serves small office premises in underserved areas with a hybrid multiplay (satellite/xDSL). This scenario corresponds to a multi-link network configuration with xDSL terrestrial link being augmented by the addition of a satellite broadband link with broadcast/multicast and caching capabilities.

For this scenario, the techno-economic analysis aims to realize several objectives:

- Evaluate the Total Cost of Ownership (TCO) of the proposed solution using a TCO cost model;
- Investigate the impact of caching popular content at the edge on the OPEX and TCO;
- Allocate the TCO to the different network services (slices) using the cost allocation model proposed for network slicing (reserved for the extension period);
- Evaluate the uncertainty of the input using sensitivity analysis (e.g. rate of caching...);
- Evaluate the different business models involving the broker

7.2 Network architecture
The network architecture of the proposed SaT5G solution for this use case consists of three different parts. The small office network, the satellite network (satellite link) and the central office/5G core network. Since in this use case satellite network complements the existing terrestrial link (i.e. the DSL link), this latter will not be included in the modelling process.

On the small office side, a user gateway has to be installed to combine the traffic coming from both the satellite and the DSL links. This user gateway uses a multilinking protocol in order to forward the traffic on the appropriate link (or a smart combination of the two links) considering the type of traffic and its required QoS and latency. This gateway is connected to the satellite terminal that receives the traffic from the satellite link. The type of the satellite terminal to install depends on the required traffic from the satellite side to complement the existing connection. If only the Download Link (DL) is concerned by this enhancement, we need to deploy a receive-only (RO) satellite terminal. Otherwise, if the Upload Link (UL) is also concerned, then a Return Channel via Satellite (RCS) type is the suitable one to install. The satellite terminal terminates the satellite connection that starts at the operator office side with the satellite gateway and goes through the satellite.
On the operator office side, an intelligent network gateway is installed in order to combine the traffic coming from the satellite gateway and the traffic coming from the DSL aggregation network. These three network components are presented in Figure 7-1 below:

![Network architecture of the multilink Sat5G solution](image)

**Figure 7-1: Network architecture of the multilink Sat5G solution**

### 7.3 Qualitative business modelling

Based on the possible business models described in section 2.1 and in section 3.3, the most likely scenario for this case is the 1-F-B in a short to medium term. However, for the long-term deployment, it is worth considering a dynamic allocation of the satellite capacity since small offices need satellite capacity only during working hours which corresponds to the 1-D-B business model. In this business model, the broker plays the role of a re-selling operator, such that he can share the satellite capacity dynamically among MNOs. He can, for example, reserve a certain bandwidth during the day to serve these small offices and during night keep it for VOD catalogue updating (use case 1). As such, the efficiency in the use of satellite resources can be realised in addition to the decrease of costs for the involved parties, since they will pay for the capacity only for a limited number of hours per day.

### 7.4 Quantitative business case evaluation: TCO model

As described in chapter 2, we use a TCO model to evaluate the economic viability of the proposed solution for the selected scenario. The cost model structure adapted to this use case is described in the first section. Section 7.4.2 details the mathematical formulation of this cost model. The model inputs and the results of the simulation are presented respectively in section 7.4.3 and 7.4.4.

#### 7.4.1 Cost model structure

The main inputs of the model are the bill of materials (BOM), the number of small offices, the minimum bitrate per office for DL and UL, the adoption rate of the proposed solution and the time horizon of the project. Those inputs feed into a cost model that consists of four sub-models in alignment with the network architecture components. After the calculation of the CAPEX and OPEX for all blocks, the TCO can be derived. Hence, given the TCO as well as the number of users, the ACPU can be derived as an output of the model.
7.4.2 Mathematical formulation of the model

In this section, we will detail formulas used to calculate both CAPEX and OPEX for each sub-model following the structure of the cost model discussed in the previous section. An overview of abbreviations can be found in Table 11-1.

Cost of the small office module:

The cost of the edge incorporates the CAPEX and the OPEX of the user intelligent gateway and the satellite terminal. The cost of the satellite terminal depends on its type (RO/RCS), which in turn depends on the bitrate to be provided on the DL and UL, as discussed previously. The bitrate required from the satellite link per small office and for all the offices are calculated using formulas (Equation 7-1) and (Equation 7-3).

The satellite connection will complement the DSL connection to reach the desirable speed. Assuming that all small offices have similar needs, the required satellite capacity is:

\[
\text{Equation 7-1} \quad \text{Bitrate}_{\text{Sat}} = \text{Bitrate}_{\text{desired}} - \text{Bitrate}_{\text{DSL}}
\]

The same formula is applicable for the DL and UL.

The CAPEX of the small office module is:

\[
\text{Equation 7-2} \quad \text{CAPEX}_{\text{SO}} = \text{C}_{\text{User,GTW}} + \text{C}_{\text{ST}}
\]

Cost of the satellite network module:

In order to calculate the required total satellite capacity needed to serve these small businesses, an important factor has to be considered which is the contention ratio\(^8\). This later defines the number of users that are sharing the bandwidth at the same time. Taking this factor into account, the total satellite capacity needed is calculated using Equation 7-3:

\[
\text{Equation 7-3} \quad \text{SatCap} = \text{Number}_{\text{SO}} \times \text{Bitrate}_{\text{Sat}} \times \text{Contention}_{\text{ratio}}
\]

The main component of the satellite network costs is the OPEX which is calculated using the following formulas:

\[
\text{Equation 7-4} \quad \text{C}_{\text{satCaps}} = \text{SatCap} \times 12 \times \text{C}_{\text{satMbps}}
\]

\[
\text{Equation 7-5} \quad \text{Opex}_{\text{sat}} = \text{C}_{\text{satCaps}} + \text{P}_{\text{satGat}} \times \text{C}_{\text{watt}} + M
\]

Cost of the core network module:

For the core network or operator central office the CAPEX and OPEX are calculated like below:

\[
\text{Equation 7-6} \quad \text{CAPEX}_{\text{core}} = \text{C}_{\text{Net,GTW}} + (\text{C}_{\text{HWMbps}} \times \text{SatCap} \times \text{Rate}_{\text{ctrl,traffic}})
\]

\[
\text{Equation 7-7} \quad \text{OPEX}_{\text{core}} = (\text{P}_{\text{NetGw}} \times \text{C}_{\text{watt}}) + (\text{C}_{\text{SWMbps}} \times \text{SatCap} \times \text{Rate}_{\text{ctrl,traffic}})
\]

In addition, the total CAPEX, OPEX and TCO as well as the additional costs are calculating using the same formulas described in the Use case 2 chapter.

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\(^8\) As this factor impacts directly the cost of the satellite capacity hence the OPEX, a sensitivity analysis is foreseen to be elaborate in the final version of this document.
7.4.3 Model inputs
Inputs used to run the cost model are presented in the tables in Appendix section 11.3.

In addition, the cost model is based on several assumptions that should be made to have as realistic results as possible:

- All the small offices have the same need in term of bitrate on both DL and UL;
- The proposed SAT5G solution will be competing with 4/5G solutions;
- The adoption rate of the proposed solution is 30%.

7.4.4 Simulation and results
For this use case, we take the example of UK where there are about 3 million business sites. These businesses range hugely in type: from one-person home-based businesses, small business with several employees on one or more sites, medium enterprises which might have a mix of big and small sites and large corporates who may have large central offices and lots of small. The largest (possibly ~10% of sites) will be fed by fibre services. Probably 80-90% of sites are small, traditional served by one or two phone lines. In the UK, super-fast broadband (over 24Mps downstream) [63] has over 90% coverage and ADSL over 99% coverage but the tail of ADSL coverage can have very low rates <1Mbps. Hence, the maximum realistic small business site base for this use case would lie in the range of 5% of the overall 3 million business sites, which corresponds to 150k small offices. For these offices, satellite would be competing with alternative solutions like 4/5G.

Small businesses value good connectivity very highly as it is often mission critical to their business. However, most small business sites will have bandwidth demands much lower than the average consumer. Data, email, document sharing etc. is not that bandwidth-consuming compared to HD TV and VOD streaming which drive the consumer market. Now there will be exceptions, for example for businesses doing video editing, intensive CAD design or gaming, but this will be a small proportion of the market. In general, the proposed solution will be addressing customers who have not been covered by preferred technology, thus, they are looking for superfast broadband speeds which in the UK is set at 24Mbps downstream, upstream maybe 5-10Mbps.

We assume that the existing DSL link is one of the three following Asymmetric digital subscriber line (ADSL) [64]:

- ANSI T1.413 Issue 2, up to 8 Mbit/s and 1 Mbit/s
- G.dmt, ITU-T G.992.1, up to 10 Mbit/s and 1 Mbit/s
- Asymmetric digital subscriber line 2 (ADSL2), ITU-T G.992.3, up to 12 Mbit/s and 3.5 Mbit/s

As explained in the mathematical formulation of the model, an important factor has to be considered which is the contention ratio on the satellite link. According to [65] and [66] the typical contention ratio for satcom ranges from 10:1 to 20:1. On the ADSL connection and according to a recent study made by BT proves that the traffic peak download rate is 1.4 Mbps for a super-fast broadband connection, hence the contention ratio is around 16:1 [67] and [68]. Assuming the same contention ratio for the satellite link, we run the cost model for these different types of the ADSL links and results are represented in the following figures:
In the first iteration of the model, we run it considering that the existing DSL connection can provide up to (a) 8 Mbps, (b) 10 Mbps and (c) 12 Mbps. Hence, the satellite link has to complement the terrestrial connection with (a) 16 Mbps, (b) 14 Mbps and (c) 12 Mbps in order to reach the super-fast broadband with 24 Mbps per office. Results of this simulation are presented in Figure 7-2 (a) and show that the ACPU for the case (a) is more expensive than (b) and (c) which is because we need more satellite capacity in case (a) than in (b) and (c). Therefore, the more satellite capacity is required the higher the ACPU is. The ACPU for the three scenarios is directly affected by the satellite capacity, thus, reducing ACPU means reducing the throughput needed from the satellite link. Hence, in the second scenario we assume that 30% of the data is served from the cached data on the CDN nodes deployed next to the exchanges (see chapter 6). The cost of these CDN nodes to host the popular content has a negligible effect on the ACPU (increase of 0.3 euro). Yet, the use of the caching concept decreases the cost of the satellite capacity thus the ACPU as presented in Figure 7-2 (b). A comparison between the ACPU for the three case (a), (b) and (c) for the two scenarios without and with caching is elaborated in Table 7-1 and an ACPU reduction rate is then concluded. It shows that the use of caching technique can save up to 28% on the ACPU.

### Table 7-1: Comparison between the two considered scenarios for the three cases

<table>
<thead>
<tr>
<th></th>
<th>Existing ADSL:8 Mbps, required on satellite: 16 Mbps</th>
<th>Existing ADSL:10 Mbps, required on satellite: 14 Mbps</th>
<th>Existing ADSL:12 Mbps, required satellite: 12 Mbps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ACPU</strong></td>
<td><strong>Satellite-5G without caching</strong></td>
<td><strong>Satellite-5G with caching</strong></td>
<td><strong>ACPU reduction rate</strong></td>
</tr>
<tr>
<td></td>
<td>29 €</td>
<td>24 €</td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td>27 €</td>
<td>23 €</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>25 €</td>
<td>21 €</td>
<td>24 %</td>
</tr>
</tbody>
</table>

### 7.5 Sensitivity analysis

In the simulation of the cost model we assumed an adoption rate of 30% of the integrated SaT-5G solution in the market of the small businesses in UK. As rough calculations show its impact is significant, a sensitivity analysis on
this adoption rate is made for the baseline scenario (i.e. without caching) for the scenario (b) in which the terrestrial DSL link has a speed of 10 Mbps.

From the result presented above, we can conclude that the higher the adoption rate the less the required ACPU.

7.6 Discussion: “putting this into context”
The SaT5G solution proposed for this use case (multilink use case) is cheaper (even without caching popular content) comparing to other satellite internet providers who have similar offers for businesses. In order to have a fair comparison the cost of the complete solution should be considered i.e. the cost of the DSL connectivity plus the cost of complementing it by the satellite connectivity. According to [69] the average price of the ADSL of 10 Mbps is around 25 euro, thus in total the price of the satellite-ADSL integrated solution is around 55 euro (considering 11% as profit margin [36]). Comparing to 80 euro per month of the satellite solution provided in UK [70] and to HughesNet in USA with (60$ to 149$) for 25Mbps but with a limited data capacity (10 to 50 GB per month, exceeded data cap reduces speed to 1-3 Mbps) [71], the proposed SaT5G solutions has reasonable ACPU.

In addition, the nature of the small business use focused on upload and download of files which might be much more bursty in nature than the consumer world, which is dominated by long hold time streaming. Therefore, satellite may offer a shared access bandwidth much higher for short duration upload and download on the basis that each line is idle for most of the time. The power of the satellite for these businesses is hence the offering of a very fast, shared bandwidth pool that serves many customers effectively because of the short duration transmission bursts. In this situation, the broker as mentioned earlier can play a crucial role if the satellite operators are uncomfortable of offering dynamic satellite capacity.

7.7 Recommendation and future work
Based on the studied scenarios the main takeaways are:

- The SaT5G solution has affordable prices if we compare them to nowadays’ prices for small businesses;
- The ACPU decreases slightly with the increase of the satellite adoption rate as the number of users increases;
• Caching popular data reduces the OPEX and hence the ACPU (from 20 to 25% depending on the caching rate used);
• An agreement with the SNO should be made based on the use of satellite capacity as it is mainly used during day hours only. The broker can play a crucial role in this agreement e.g. the role of the re-seller (the third business model of the broker), if the SNO do not have the intention to sell their satellite capacities in a dynamic way.

These results can give insights to operators who want to enhance their connectivity and provide the super-fast broadband in underserved regions. The use of satellite communications combining with the existing poor DSL connections demonstrate reasonable costs.

An interesting future analysis could be the economic and environmental benefits of using virtualization to integrate the VSAT modem with the home gateway.
8 Use case 4: 5G Moving platform backhaul

8.1 Introduction

This set of scenarios can be summarised as providing high-speed backhaul connectivity to individual moving terminals on airplanes, vehicles, trains, vessels (including cruise ships and other passenger vessels) or even future driverless cars, with the ability to multicast the same content (e.g. video, HD and UHD TV, as well as other non-video data) across a large coverage area (e.g. for local storage and consumption) and provide efficient broadband access connectivity from or towards these moving platforms.

It should be noted that both satellite stand-alone backhauling and hybrid multi-play, i.e. the satellite link acting as a complement of existing terrestrial infrastructure, can be envisaged depending on the Scenario and the type of targeted platform [1].

The selected SaT5G scenario is providing broadband access for passengers on commercial airliners, alongside additional individual media requests. This scenario proposes a bi-directional broadband access for each passenger for private use which is transparent to the moving platform. The network requests are therefore individual and proper to each passenger's activities. This scenario represents the 5G cell backhauling on the move. The passenger would use their own device(s) as they do on the ground. In addition, they could use the devices provided by the companies (e.g. seats screens) to access only the local media content (i.e. from the entertainment catalogue) or remote servers through pre-installed applications.

For this scenario, the techno-economic analysis aims to realize several objectives:

- Evaluate the Total Cost of Ownership (TCO) of the proposed solution using a TCO cost model. This model is described in section 2.2;
- Investigate the impact of caching popular content at the edge on the OPEX and TCO;
- Evaluate the uncertainty of the input using sensitivity analysis (e.g. rate of caching...) as described in section 2.4;
- Investigate the different business models for offering the inflight connectivity and pricing strategies;
  - Benchmark the findings with the inflight connectivity prices adopted nowadays.

8.2 Network architecture

The network architecture of providing broadband access to on board passengers consists of 4 main sub-networks: (1) the aircraft network, (2) satellite network, (3) airline data centre and (4) the 5G core network. The aircraft network is composed of the media server where the popular content will be cached, three Wi-Fi access points (WAPs), one 5G gNB, a switch and the satellite modem and antenna. On the other hand, on the ground we have the data centre of the airline company that provides the service which is connect by its turn to the 5G core network. The aircraft and the ground networks are connected via a MEO satellite link which starts with the satellite terminal on the aircrafts and terminates by the satellite gateway which is connected to the airline company via a VPN. The network architecture of the proposed solution is presented in the figure below:
8.3 Qualitative business modelling

Based on the possible business models described in section 2.1 and in section 3.3, the most likely scenario for this case is the 1-F-B in a short-term period or the 1-D-B in the mid to long term. The broker is needed in both cases because for example in long-haul flights the aircraft can move from one satellite system provider to another, hence, the broker is the easiest way to get the best offer per SNO and per region. In addition, the satellite capacity needed for this scenario has a variable pattern along the day, as well as an indication of how many flights per day the aircraft will perform. Therefore, the suitable business model in the medium to long term reservation is the 1-D-B, which means the MNO asks the broker to reserve a dynamic satellite capacity according to his need. The broker in this case take the role of a re-seller as explained in section 3.3.3.

However, these business models are identified in the light of resource management. Yet, for providing the inflight connectivity service other business models exists and per business model different pricing schemes can be applied. The possible business models to provide the service to the end user are discussed in section 8.4.4.

8.4 Quantitative business case evaluation: TCO model

As described in chapter 2, we use a TCO model to evaluate the economic viability of the proposed solution for the selected scenario. The cost model structure adapted to this use case is described in the first section. Section 8.4.2 details the mathematical formulation of this cost model. The model inputs and the results of the simulation are presented respectively in section 8.4.3 and 8.4.4.

8.4.1 Cost model structure

The main inputs of the model are the bill of materials (BOM), the number of passengers/users, the minimum bitrate per user, the flight duration, number of flights per year and the time horizon of the project. Those inputs feed into a cost model that consists of four sub-models in alignment with the network architecture components. After the calculation of the CAPEX and OPEX for all blocks, the TCO can be derived. Hence, given the TCO as well as the number of users, the ACPU can be derived as an output of the model.

8.4.2 Mathematical formulation of the model

In this section, we will detail formulas used to calculate both CAPEX and OPEX for each sub-networks following the structure of the cost model discussed in the previous section and the network architecture presented in section 8.2. An overview of abbreviations can be found in Table 11-1.
Cost of the aircraft network:

The cost of the aircraft network incorporates the CAPEX of the 5G gNB, WAPs, the media server and the CAPEX of the satellite terminal and the OPEX of all the network components. The CAPEX and OPEX of the aircraft network are calculated using the following formulas:

\[ \text{Equation 8-1 } \text{CAPEX}_{\text{NetAircraft}} = N_{gNB} \times \text{CAPEX}_{gNB} + N_{WAP} \times \text{CAPEX}_{WAP} + \text{CAPEX}_{ST} + \text{CAPEX}_{MediaServ} \]

\[ \text{Equation 8-2 } \text{OPEX}_{\text{NetAircraft}} = (N_{gNB} \times P_{gNB} + N_{WAP} \times P_{WAP} + P_{ST} + P_{MediaServ}) \times C_{\text{watt}} + M \]

Cost of the satellite network:

The cost of the satellite link depends a lot on how much satellite capacity is needed to serve the aircraft users.

The total satellite capacity needed is:

\[ \text{Equation 8-3 } \text{SatCap} = N_{u} \times B_{u} \]

The OPEX of the satellite network is calculated using the following formulas:

\[ \text{Equation 8-4 } C_{\text{satCaps}} = \text{SatCap} \times 12 \times C_{\text{satMbps}} \]

\[ \text{Equation 8-5 } \text{Opex}_{\text{sat}} = C_{\text{satCaps}} + P_{\text{satGat}} \times C_{\text{watt}} + M \]

Cost of the airline data centre:

The cost of the airline data centre is mainly the CAPEX of the servers used and the OPEX of them which is the power consumption and the maintenance costs.

Cost of the 5G core network:

For the core network or operator central office the CAPEX and OPEX are calculated like below:

\[ \text{Equation 8-6 } \text{CAPEX}_{\text{core}} = C_{\text{SWMbps}} \times \text{SatCap} \times \text{Rate}_{\text{ctrl_traffic}} \]

\[ \text{Equation 8-7 } \text{OPEX}_{\text{core}} = C_{\text{SWMbps}} \times \text{SatCap} \times \text{Rate}_{\text{ctrl_traffic}} \]

In addition, the total CAPEX, OPEX and TCO as well as the additional costs are calculating using the same formulas described in the Use case 2 chapter.

8.4.3 Model inputs

Inputs used to run the cost model are presented in the tables in Appendix section 11.4.

In addition, the cost model is based on several assumptions that should be made to have as realistic results as possible:

- We assume the use of MEO satellite within the O3B constellation;
- Satellite handovers within O3B constellation are pure satellite procedures and they do not affect the 5G networks, hence we consider only one satellite gateway to communicate with 5G core network;
- We assume that the airplane flies within the coverage of MEO satellites;
- When the ground gNB that the UE is attached to hands his traffic to the gNB located on board, different business entities are involved. This might need a different process comparing to the normal handover
within 5G networks (because the new gNB is backhauled by satellite connectivity). However, we will model this case as a normal handover within 5G network context (note that in reality it might be different because of the satellite link (less cap and more latency));

- We use a combination of small cells and Wi-Fi access points (WAP). WAP are mainly used for the local content, but they can carry traffic to the 5G core network.

8.4.4 Simulation and results

The scenario considered here is a flight from Munich to Portugal. We assume that the airplane flies within the coverage of MEO satellites. Since there are specific locations for satellite gateway within the O3B constellation e.g. Nemea (Greece), Sintra (Portugal) etc. and in this scenario, we work with the satellite gateway located in Sintra in Portugal. The virtualized 5G network core is located in the airline data centre in Munich. All the model inputs are recapitulated in Appendix section 11.4.

Assuming a caching rate of 40%, the results of the studied scenarios are presented in the following figure:

![Figure 8-2: TCO and other cost components of the SaT5G proposed solution](image)

The proposed solution with a caching rate of 40% results in 3.5 euro per user as an ACPU and 0.1 euro per 100 MB of data consumption. A sensitivity analysis will be elaborated on the caching rate in section 8.5.

The different business models proposed for providing the inflight connectivity with the SaT5G solution are recapitulated in the following table:
Table 8-1: Possible business model for providing inflight connectivity

<table>
<thead>
<tr>
<th>Business models</th>
<th>SHORT DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wholesale model</td>
<td>The airline buys the project from an MNO and sells the service to end users.</td>
</tr>
<tr>
<td>Retail model</td>
<td>The MNO installs the project on the platform provided by the airline and sells the service directly to end users.</td>
</tr>
<tr>
<td>Sponsorship model</td>
<td>The airline buys the project from an MNO and generates revenues by selling sponsorship projects. End users are offered the service for free.</td>
</tr>
<tr>
<td>Freemium wholesale model</td>
<td>The airline buys the project from an MNO and sells the service to premium end users. Limited service is offered to free users.</td>
</tr>
<tr>
<td>Freemium retail model</td>
<td>The MNO installs the project on the platform provided by the airline and sells the service directly to premium end users. Limited service is offered to free users.</td>
</tr>
<tr>
<td>Complementary service model</td>
<td>The airline buys the project from an MNO and offers the service for free to all passengers.</td>
</tr>
</tbody>
</table>

In addition, the feasible pricing models applicable for these business models are identified in the table below:

Table 8-2: Feasible pricing models per business model

<table>
<thead>
<tr>
<th>Business model</th>
<th>Feasible considered pricing models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wholesale</td>
<td>Data-based, subscription-based, tiered-bandwidth, per-flight, time-based pricing</td>
</tr>
<tr>
<td>Retail</td>
<td>Data-based, subscription-based, tiered-bandwidth, per-flight, time-based pricing</td>
</tr>
<tr>
<td>Sponsorship</td>
<td>Average sponsorship deal size per month</td>
</tr>
<tr>
<td>Freemium wholesale</td>
<td>Subscription-based, per-flight pricing</td>
</tr>
<tr>
<td>Freemium retail</td>
<td>Subscription-based, per-flight pricing</td>
</tr>
<tr>
<td>Complementary service model</td>
<td>Indirect increase in ticket price</td>
</tr>
</tbody>
</table>
8.5 Sensitivity analysis

As discussed previously, the assumption on the caching rate has a significant impact on the results since it affects the required satellite capacity to serve the aircraft. Therefore, in this section we study the impact of the caching rate variation on the ACPU.

![Variation of the ACPU in function of caching rate](image)

*Figure 8-3: Impact of the caching rate on the ACPU*

It is clear from Figure 8-3 that the ACPU is and as predicted strongly related and affected by the caching rate assumed. The ACPU decreases when the caching rate increases, since we serve the users more from the cached data on the media server located on the aircraft than from the traffic that has to be sent via the satellite link. Thus, we pay less for the satellite capacity.

8.6 Discussion: “putting this into context”

In order to validate the findings of this use case, a benchmarking with the existing inflight connectivity service is made and presented in Table 8-3.

<table>
<thead>
<tr>
<th>Airline</th>
<th>Provider</th>
<th>Business model(s)</th>
<th>Price</th>
<th>Pricing model(s)</th>
<th>Average price per MB</th>
<th>Comparison with SaT5G price (30% as profit margin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aer Lingus [72]</td>
<td>Panasonic Avionics, Aeromobile,</td>
<td>Retail, Complementary service</td>
<td>Economy class: €6.95 / 50 MB; €13.95 / 120 MB; €29.95 / 270 MB</td>
<td>Data-based pricing</td>
<td>€0.122</td>
<td>74 times more expensive than the SaT5G costs.</td>
</tr>
<tr>
<td></td>
<td>Deutsche Telekom</td>
<td></td>
<td>Business class: free</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Canada [73]</td>
<td>Gogo</td>
<td>Retail</td>
<td>$49.95 / 1 month; $5 / 1 hour; $14 / 24 hours</td>
<td>Subscription-based pricing, time-based pricing</td>
<td>€0.017</td>
<td>12 times more expensive than the SaT5G costs.</td>
</tr>
</tbody>
</table>
From Table 8-3, we can conclude that under the taken assumptions the SaT5G solution is cheaper comparing to other inflight internet providers. However, it is noteworthy, that in the cost model of the SaT5G solution the cost of the 5G mobile network spectrum is not included and it might be that the existing services count the spectrum costs in the price of the service in order to pay off this high cost.

8.7 Recommendation and future work

This use case investigates the cost and the possible business models for providing broadband service to on-board users. The main takeaways from this techno-economic analysis are:

- Providing inflight broadband service with a good throughput per user (2 to 5 Mbps) with reasonable prices is feasible thanks to the integration of satellite communications into the 5G network.
- Caching popular data reduces the OPEX and hence the ACPU (from 25 to 32% depending on the caching rate used).
- Different business models are possible for the proposed solution based on who will provide the service to the end user e.g. wholesale model, retail, sponsorship etc....
- Per identified business model many feasible pricing’ schemes are identified like Data-based, subscription-based, tiered-bandwidth, per-flight, time-based pricing etc...

As a future work we aim to evaluate quantitively the different business models and identify for each business model the most profitable pricing model. The extension of this analysis to other moving platforms such as trains and ships would be an interesting piece of follow-up work.
9 Conclusion and recommendations

This deliverable presents the prefinal results of the business modelling work of the Sat5G project.

Based on a generic business modelling methodology, different theoretical models were developed for the specific case of evaluating the economic viability and market strategy of integrated satellite-5G networks. First, given that integrated networks inherently lean on the collaboration between multiple stakeholders, each with different backgrounds, the role of an intermediate management broker was proposed to handle the interactions between mobile and satellite operators. More specifically, three business models were proposed, ranging from a broker as a pure negotiator to a broker that takes up the role as a re-selling operator. They were assessed from both technical and techno-economic point of view. The main conclusion is that the business model will probably be decided by the type of use case envisaged, as well as who takes up the main risk.

Secondly, a dedicated Total Cost of Ownership model was set up, allowing to estimate costs of RAN, satellite and core network. The main structure of the model was built in a generic way, though it was adapted for each use case to include use-case specific requirements and generate the most interesting results. As techno-economic results depend strongly on the quality and accuracy of the input parameters, specific scenario and sensitivity analyses were executed to increase the confidence interval of the obtained results.

Finally, in order to deliver end-to-end services of an integrated network, end-to-end slices should be set up as well. Though this poses technical challenges, this deliverable tackles the economic challenges by drafting a methodology that allows to allocate the use of resources across the network to the different slices (or services) using it. Two dedicated parts build this methodology: allocation of the throughput and allocation of the core network. Though the former is rather straightforward based on throughput and allocation of the core network. Though the former is rather straightforward based on throughput and QoS requirements of different slices, the latter builds on an assessment of the traffic generated by both control and data plane network functions.

This generic methodology was applied on four use cases that were identified earlier in the project. In what follows, these will all be described shortly, and our main recommendations highlighted.

The aim of the first use case is to study the affordability of the Sat-5G integrated solution to enhance the terrestrial network links incapable to provide live streaming services and high capacity bursty traffic. Results have shown reasonable average cost per user and significant bandwidth savings. These results vary from one scenario to another and based on the studied scenarios the main takeaways are:

- Using satellite multicast decreases the OPEX for the integrated SaT5G solution which implies a decrease in the ACPU as well;
- The ACPU is higher in low population density areas than in high population density areas (e.g. France vs Botswana), since we need to install more nodes to cover the sparse households’ clusters while having a smaller number of users;
- The total bandwidth saving increases with the increase of the number of CDN nodes installed because we save more traffic on the “poor” links with installing more nodes;
- Taking the status of the entire network into account reduces the total number of CDN nodes required, hence reduces also the cost.
The second use case consists on providing broadband connectivity where it is difficult or not (yet) possible to deploy terrestrial connections to cell towers, for example, coverage on lakes, islands, mountains, rural areas, isolated areas or other areas that are best or only covered by satellites; across a wide geographic region. The analysis was performed on the specific scenario satellite backhaul to individual cell towers. The main takeaways and recommendations from the business modelling of this use case are:

- The proposed satellite-5G solution is economically viable without caching for a modest bitrate per user and with caching for a good bitrate per user (when comparing to the WTP of the end user);
- Caching popular content to the edge saves from 40% to more than 50% of the OPEX depending on the provided bitrate per user and the caching rate used;
- Installing caching technology is not useful when a low throughput per user in rural areas is expected (lower than 200 kbps);
- The ACPU is very sensitive to the population density variation (i.e. to the number of users).
- The CAPEX is only slightly affected by the variation of caching rate, however the OPEX is very sensitive the caching rate.

The third use case consider the multilinking solution using satellite to provide super-fast broadband in underserved areas as a complement to the existing poor DSL lines. Based on the studied scenarios the main takeaways are:

- The SaT5G solution has affordable prices if we compare them to nowadays’ prices for small businesses;
- The ACPU decreases slightly with the increase of the satellite adoption rate as the number of users increases;
- Caching popular data reduces the OPEX and hence the ACPU (from 20 to 25% depending on the caching rate used);
- An agreement with the SNO should be made based on the use of satellite capacity as it is mainly used during day hours only. The broker can play a crucial role in this agreement e.g. the role of the re-seller (the third business model of the broker), if the SNO do not have the intension to sell their satellite capacities in a dynamic way.

This Fourth and last use case investigates the cost and the possible business models for providing broadband service to users on-board the aircraft. The main takeaways from this techno-economic analysis are:

- Providing inflight broadband service with a good throughput per user (2 to 5 Mbps) with reasonable prices is feasible thanks to the integration of satellite communications into the 5G network;
- Caching popular data reduces the OPEX and hence the ACPU (from 25 to 32% depending on the caching rate used);
- Different business models are possible for the proposed solution based on who will provide the service to the end user e.g. wholesale model, retail, sponsorship etc.;
- Per identified business model many feasible pricing’ schemes are identified like Data-based, subscription-based, tiered-bandwidth, per-flight, time-based pricing etc...

As a future work a quantitative evaluation of the different business models has to be considered besides the identification for each business model what is the most profitable pricing model. The extension of this analysis to other moving platforms such as trains and ships would be an interesting piece of follow-up work.
In addition, for all use cases the intention is to run more sensitivity analysis where we vary multiple parameters at the same time to investigate how sensitive are the results of the project to certain parameters.
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11 Appendix

This appendix provides an overview of the abbreviations and inputs used in the cost model.

Table 11-1: Nomenclature

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Designation</th>
<th>Nomenclature</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Br_u )</td>
<td>bitrate per user</td>
<td>( H_u )</td>
<td>average active hours per user</td>
</tr>
<tr>
<td>( Br_s )</td>
<td>bitrate per site</td>
<td>( N_u )</td>
<td>number of users</td>
</tr>
<tr>
<td>( Cov_a )</td>
<td>coverage area</td>
<td>( C_{satMbps} )</td>
<td>cost of 1 Mbps per month via satellite link</td>
</tr>
<tr>
<td>( Cov_{enb} )</td>
<td>eNB coverage</td>
<td>( C_{satCapS} )</td>
<td>cost of satellite capacity for a site S</td>
</tr>
<tr>
<td>( Bw_{enb} )</td>
<td>eNB bandwidth</td>
<td>( Br_T )</td>
<td>bitrate per site for traffic control and overhead</td>
</tr>
<tr>
<td>( N_{enb} )</td>
<td>number of eNB</td>
<td>( M )</td>
<td>maintenance costs</td>
</tr>
<tr>
<td>( C_{enb} )</td>
<td>cost of eNB</td>
<td>( P_{satGat} )</td>
<td>power consumption satellite gateway per year</td>
</tr>
<tr>
<td>( C_T )</td>
<td>cost of the tower</td>
<td>( C_{watt} )</td>
<td>cost of energy</td>
</tr>
<tr>
<td>( N_s )</td>
<td>number of servers</td>
<td>( N_{stg} )</td>
<td>number of storages</td>
</tr>
<tr>
<td>( Mec_{mng} )</td>
<td>cost of MEC software management</td>
<td>( C_{stg} )</td>
<td>cost of storage</td>
</tr>
<tr>
<td>( C_s )</td>
<td>cost of server</td>
<td>( N )</td>
<td>number of sites served by the satellite gateway</td>
</tr>
<tr>
<td>( C_{Inst} )</td>
<td>cost of hardware installation</td>
<td>( C_{Hw} )</td>
<td>cost of the hardware</td>
</tr>
<tr>
<td>( OvhdC )</td>
<td>overhead costs</td>
<td>( P_{eNBs} )</td>
<td>power consumption of the eNBs per year</td>
</tr>
<tr>
<td>( Site_{rental} )</td>
<td>Cost of renting the site for deploying the eNBs and the satellite terminal per year</td>
<td>( P_{ST} )</td>
<td>power consumption of the satellite terminals per year</td>
</tr>
<tr>
<td>( C_{satCapS,Caching} )</td>
<td>cost of satellite capacity for a site S with caching data on the edge</td>
<td>( N_{\text{channels}} )</td>
<td>Number of live channels provided</td>
</tr>
<tr>
<td>( \text{Layer(i)}_{speed} )</td>
<td>The speed of the layer number i</td>
<td>( \text{Bitrate}_{Live} )</td>
<td>The required bitrate for the live streaming service</td>
</tr>
<tr>
<td>( \text{Storage}_{VOD} )</td>
<td>The part of the VOD catalogue that has to be updated</td>
<td>( \text{VODcat}_{size} )</td>
<td>The size of the VOD catalogue in hours</td>
</tr>
<tr>
<td>( \text{Nb}_{sec,1hr} )</td>
<td>Number of seconds in one hour</td>
<td>( \text{Bitrate}_{VOD} )</td>
<td>The required bitrate for updating the VOD catalogue</td>
</tr>
<tr>
<td>( \text{Nb}_{update,1hr} )</td>
<td>Number of updating hours during night</td>
<td>( \text{Bitrate}_{CDN} )</td>
<td>The required bitrate for serving one CDN node</td>
</tr>
<tr>
<td>( \text{CDN}_{PwrConsump} )</td>
<td>Power consumption of all the CDN node equipment</td>
<td>( \text{Bitrate}_{Sat} )</td>
<td>The required bitrate from the satellite link</td>
</tr>
<tr>
<td>( \text{Bitrate}_{desired} )</td>
<td>The required bitrate to serve one small office</td>
<td>( \text{Bitrate}_{DSL} )</td>
<td>The existing bitrate of the DSL link</td>
</tr>
<tr>
<td>( \text{Nb}_{SO} )</td>
<td>Number of small offices</td>
<td>( C_{\text{User,GTW}} )</td>
<td>Cost of the user gateway</td>
</tr>
<tr>
<td>( C_{Net,GW} )</td>
<td>Cost of the network gateway</td>
<td>( \text{Rate}_{ctrl,traffic} )</td>
<td>Percentage of the control traffic from the overall traffic</td>
</tr>
<tr>
<td>( P_{Net,GW} )</td>
<td>Power consumption of the network gateway</td>
<td>( C_{HW,Mbps} )</td>
<td>Cost per Mbps of control traffic of the hardware of the 5G core network</td>
</tr>
</tbody>
</table>
### 11.1 Use case 1 inputs:

*Table 11.2 Inputs for use case 1 modelling*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subscribers for the operator in France [58]</td>
<td>24M subscribers</td>
</tr>
<tr>
<td>Number of subscribers for the operator in Botswana [59]</td>
<td>568000 subscribers</td>
</tr>
<tr>
<td>Video subscribers' rate</td>
<td>30%</td>
</tr>
<tr>
<td>Peak time usage rate</td>
<td>40%</td>
</tr>
<tr>
<td>Number of live channels [55]</td>
<td>100 but only 5 channels represent 80% of the viewing in all regions</td>
</tr>
</tbody>
</table>
| VOD catalogue size [55]                                                  | • 6000 hours but 60 hours of these content represent 80% of the viewing in all regions  
| Videos specification [55]                                               | • Live and VOD channels are available in MPEG-DASH, encoded in HEVC, and have the following layers available: 4 Mbps; 3 Mbps; 2 Mbps; 1 Mbps and 500 kbps. |
| MEC infrastructure costs: [75]                                           | • Server                                                            |
|                                                                          | • 2 x 32 GB RAM                                                     |
|                                                                          | • Physical storage: 2 x 300GB disks                                  |
|                                                                          | • 8 vCPU at 2Ghz                                                    |
|                                                                          | • Licence cost                                                       |
|                                                                          | ~700€                                                               |
|                                                                          | ~800€                                                               |
|                                                                          | ~240€                                                               |
|                                                                          | Free for VMWare                                                     |
|                                                                          | 12k€                                                                |
| Transcaster in head-end                                                  | 60k€                                                                |
MEC infrastructure power consumption [55] 3022.2 kWh per year.

The rate of the control traffic from the overall user’s traffic 10%

### 11.2 Use case 2 inputs:

**Table 11-3: General inputs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low-end scenario</th>
<th>Likely scenario</th>
<th>Premium scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation period</td>
<td></td>
<td>5 years (2020-2024)&lt;sup&gt;9&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td></td>
<td>78.5 km&lt;sup&gt;2&lt;/sup&gt; &lt;sup&gt;6&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Average busy hour data rate per site</td>
<td>53.2 Mbps&lt;sup&gt;6&lt;/sup&gt;</td>
<td>210 Mbps&lt;sup&gt;6&lt;/sup&gt;</td>
<td>9450 Mbps&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>Average active hours per user</td>
<td></td>
<td>9&lt;sup&gt;10&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Active users rate (%)</td>
<td></td>
<td>80&lt;sup&gt;6&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Cost of 1 kW</td>
<td></td>
<td>0.114 euro [76]</td>
<td></td>
</tr>
</tbody>
</table>

**Table 11-4: Edge inputs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RAN</strong></td>
<td></td>
</tr>
<tr>
<td>Macro cell: 3 antennas, 1BBU,</td>
<td>25-30k €</td>
</tr>
<tr>
<td>Software upgrades and maintenance</td>
<td></td>
</tr>
<tr>
<td>Macro cell bitrate</td>
<td>Maximal deployment is 5 * 3 sectors per eNB, (5<em>3</em>140= 840Mbps) [55]</td>
</tr>
<tr>
<td>building, rigging and materials (tower</td>
<td>10k $ [77]</td>
</tr>
<tr>
<td>10m)</td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td>2.1 kW [55]</td>
</tr>
<tr>
<td><strong>Satellite terminal (ST)</strong></td>
<td></td>
</tr>
<tr>
<td>Cost of ST</td>
<td>4K $ [78]</td>
</tr>
<tr>
<td>Capacity of the satellite link/ST:</td>
<td>150 [78]</td>
</tr>
<tr>
<td>Mbps</td>
<td></td>
</tr>
<tr>
<td>Satellite terminal power consumption</td>
<td>438 kWh per year</td>
</tr>
<tr>
<td>Air conditioning</td>
<td>~500 € [79]</td>
</tr>
</tbody>
</table>

---

<sup>9</sup> Use case definition

<sup>10</sup> These assumptions are derived based on Internet research, so may be realistic but not precise.
Common power consumption: cooling etc... | 30835 kWh per year
---|---
Edge maintenance | 10% of CAPEX [34]

**Table 11-5: Satellite network inputs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite capacity cost ($/Mbps/month)</td>
<td>15$-7$ (2020-2025) [77]</td>
</tr>
<tr>
<td>Satellite gateway infrastructure (€)</td>
<td>Cost of satellite gateway is included in the cost of satellite capacity</td>
</tr>
<tr>
<td>Maintenance</td>
<td>10% of CAPEX [34]</td>
</tr>
</tbody>
</table>

**Table 11-6: 5G core network inputs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of 5G core network for hardware (€): HW</td>
<td>5 to 6 euro per Mbps</td>
</tr>
<tr>
<td>Cost of 5G core network for software (€): SW</td>
<td>30 to 35 euro per Mbps</td>
</tr>
</tbody>
</table>

**Table 11-7: MEC inputs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Caching rate on the edge</td>
<td>20% - 80%: 20% of popular content will be stored and 80% of user requests are served from cached data.</td>
</tr>
<tr>
<td>Popular content volume</td>
<td>YouTube catalogue: $10^9$ MB as a total volume of popular content, which is based on $10^8$ MB YouTube movies, each having a size of 10MB [46]</td>
</tr>
<tr>
<td>MEC infrastructure costs: [75]</td>
<td>~700€</td>
</tr>
<tr>
<td></td>
<td>~800€</td>
</tr>
<tr>
<td></td>
<td>2800€</td>
</tr>
<tr>
<td></td>
<td>Free for VMWare</td>
</tr>
<tr>
<td></td>
<td>12k€</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------------------------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Management software:</td>
<td></td>
</tr>
<tr>
<td>- 8 vCPU at 2.6Ghz,</td>
<td></td>
</tr>
<tr>
<td>- 32 GB of RAM,</td>
<td></td>
</tr>
<tr>
<td>- 600 GB of disk, with the licence</td>
<td>60 k€ to cover 50 sites 11</td>
</tr>
<tr>
<td>MEC infrastructure power consumption</td>
<td>3022.2 kWh per year2</td>
</tr>
</tbody>
</table>

**Table 11-8: Back of the envelope calculation for the Fiber-5G solution**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumptions</td>
<td></td>
</tr>
<tr>
<td>- Area of 100 km2,</td>
<td></td>
</tr>
<tr>
<td>- 100 km far from the nearest operator central office;</td>
<td></td>
</tr>
<tr>
<td>- 1300 users;</td>
<td></td>
</tr>
<tr>
<td>- price of m of fiber 50 euro;</td>
<td></td>
</tr>
<tr>
<td>- max coverage of a macro cell is $5^2\times\pi=78.5$ km$^2$;</td>
<td></td>
</tr>
<tr>
<td>Price of the Fiber</td>
<td>5000000</td>
</tr>
<tr>
<td>Number of base stations</td>
<td>2</td>
</tr>
<tr>
<td>Price of base station</td>
<td>25000</td>
</tr>
<tr>
<td>Price of BSs</td>
<td>500000</td>
</tr>
<tr>
<td>Length of fiber between BSs</td>
<td>5000</td>
</tr>
<tr>
<td>Price of fiber to connect BSs</td>
<td>250000</td>
</tr>
<tr>
<td>Total price: CAPEX</td>
<td>5275000</td>
</tr>
<tr>
<td>ACPU/month for 5 years</td>
<td>67.7 euro</td>
</tr>
</tbody>
</table>

11.3 Use case 3 inputs:

**Table 11-9: Use case 3 inputs**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of offices [55]</td>
<td>150k</td>
</tr>
<tr>
<td>Throughput per office [63]</td>
<td>24Mbps DL (5-10 Mbps)</td>
</tr>
<tr>
<td></td>
<td>Poor DSL connection 1 Mbps UL</td>
</tr>
<tr>
<td>Cost of satellite terminal [55]</td>
<td>£190</td>
</tr>
<tr>
<td>Cost of intelligent user gateway [55]</td>
<td>90 euro</td>
</tr>
<tr>
<td>Cost of intelligent network gateway: nokia 7750 service router [80]</td>
<td>20383</td>
</tr>
</tbody>
</table>

---

11 These assumptions are derived based on Internet research, so may be realistic but not precise.
<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption network gateway [80]</td>
<td>4.6 kwh</td>
</tr>
</tbody>
</table>
| Existing connection [64]                                             | Asymmetric digital subscriber line (ADSL):  
|                                                                     | • ANSI T1.413 Issue 2, up to 8 Mbit/s and 1 Mbit/s  
|                                                                     | • G.dmt, ITU-T G.992.1, up to 10 Mbit/s and 1 Mbit/s  
|                                                                     | • Asymmetric digital subscriber line 2 (ADSL2), ITU-T G.992.3, up to 12 Mbit/s and 3.5 Mbit/s  |
| Adoption rate                                                        | 30%                       |
| The rate of the control traffic from the overall user’s traffic      | 10%                       |

### 11.4 Use case 4 inputs:

*Table 11-10: Use case 4 inputs*

<table>
<thead>
<tr>
<th>Aircraft Network</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi-Fi AP: Aero-adapted [55]</td>
<td>5 000 – 10 000 €</td>
</tr>
</tbody>
</table>
| 5G Small Cell: Aero-adapted gNB  
HW: Ettus B210 SDR, Intel Nuc Server with 4 cores CPU, 16 GB RAM and 500 GB Disk  
SW: OAI 4G CN srsLTE [55] | 50 000 – 100 000 €   |
| Number of gNBs      | 1                      |
| Number of WAPs      | 3                      |
| Media Server        | 30 000 – 50 000 €      |
| HW: COTS            |                        |
| SW: Open Source / Proprietary [55] |                      |
| Number of media servers | 1 for caching and 1 for media server |
| Caching license [55] | 12 000€                |
| 5G Satellite network |                       |
| VSAT  
SES AvL antenna + radome [55] | 200 000 – 500 000€    |
<p>| 5G Core Network     |                        |
| Power usage: 5G      | 14 907 kWh / year      |
| Aircraft Network     | Quantity               |
| Power usage: Servers | 298 kWh / year         |
| Power usage: gNB     | 0.7 kWh / year         |</p>
<table>
<thead>
<tr>
<th>Aircraft Network</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>5G Satellite network</td>
<td>Quantity</td>
</tr>
<tr>
<td>Power usage: VSAT</td>
<td>447 kWh / year</td>
</tr>
<tr>
<td>Satellite capacity [55]</td>
<td>75 -&gt; 35 between 2020-2025 $ / Mbps / user</td>
</tr>
<tr>
<td>General</td>
<td>Quantity</td>
</tr>
<tr>
<td>VPN: BT [55]</td>
<td>8087 €: 20K euro for the VPN divided by the number of flights</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flight</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of passengers [81]</td>
<td>200</td>
</tr>
<tr>
<td>Fraction of passengers that connect [82]</td>
<td>85%</td>
</tr>
<tr>
<td>Fraction of flight duration with effective internet use [83]</td>
<td>30%</td>
</tr>
<tr>
<td>Bit rate per user</td>
<td>3 Mbps</td>
</tr>
<tr>
<td>Caching rate</td>
<td>40%</td>
</tr>
<tr>
<td>Number of users per WAP [55]</td>
<td>50</td>
</tr>
<tr>
<td>Average number of airplane cycles (every landing or take-off is considered as a cycle) (Boeing 747) [84]</td>
<td>35 000</td>
</tr>
<tr>
<td>Average lifetime airplane (Boeing 747) [84]</td>
<td>27 years</td>
</tr>
</tbody>
</table>

Table 11-11: Inputs for the baseline scenario

11.5 5G control plane modelling: AMF and SMF

Following the same reasons argued in [85], [86] and [87], we assume that the most frequent procedures are the service request (SR), the service release request (SRR) and the X2-based handover (HO). Following the reasoning presented above, both AMF and SMF are CPU-intensive, which allows us to consider the CPU power as the main cost driver. Therefore, in the proposed model, only the CPU power will be calculated, from which we will derive the RAM and storage by proportionality.

As explained previously, the signaling traffic modelling for AMF and SMF requires the following inputs: the procedures’ frequency, number of instructions per procedure message and the number of exchanged messages per procedure for both AMF and SMF. In the next subsections we detail each input apart and explain from where derive it.

1. Procedures frequency:

There are two different assumptions regarding the frequency of the considered procedures. On the one hand, assuming a user inactivity of 10 s, authors in [88] calculated by the mean of a mathematical framework the signaling
rates per user equipment for each signaling procedures for the vMME as presented in the table below labelled with frequency 2. On the other hand, authors in [85] derived the SR, SRR and HO frequencies from an operational network measurement as presented in Table 11-12 with frequency 1.

Table 11-12: frequency of the considered control procedures

<table>
<thead>
<tr>
<th>Procedures</th>
<th>Service Request</th>
<th>Service Release</th>
<th>X2-based HO</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency 1: nb of events per user/s</td>
<td>0.00126</td>
<td>0.00126</td>
<td>0.00112</td>
<td>[85]</td>
</tr>
<tr>
<td>Frequency 2: nb of events per user/s</td>
<td>0.0045</td>
<td>0.0045</td>
<td>0.0012</td>
<td>[88]</td>
</tr>
</tbody>
</table>

2. **Number of instructions per procedure message:**

We assume that the number of run instructions for the different control messages are the same as in [86] and [87], as presented in table below:

Table 11-13: number of instructions per user per procedure

<table>
<thead>
<tr>
<th>Procedures</th>
<th>Service Request</th>
<th>Service Release</th>
<th>X2-based HO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of instructions per procedure</td>
<td>3580000</td>
<td>3200000</td>
<td>2140000</td>
</tr>
</tbody>
</table>

3. **Number of instructions per procedure for AMF and SMF:**

In order to model the contribution of both AMF and SMF in the signaling traffic, we use the 3GPP specification document [89] describing the sequence diagrams for each control procedure, and from there we counted the number of messages handling by AMF versus those handled by SMF for each procedure. For each procedure, several
assumptions for service request\textsuperscript{12}, service release request\textsuperscript{13} and X2-based handover\textsuperscript{14} procedures were made in order to count these numbers.

The contribution of both AMF and SMF per procedure are presented in the table below:

\textit{Table 11-14: number of messages for each procedure for both AMF and SMF}

<table>
<thead>
<tr>
<th>Procedures</th>
<th>Service Request</th>
<th>Service Release</th>
<th>X2-based HO</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMF: number of exchanged messages</td>
<td>0.533333333</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>SMF: # number of exchanged messages</td>
<td>0.4</td>
<td>0.8</td>
<td>0.666666667</td>
</tr>
</tbody>
</table>

\textbf{11.5.1 Mathematical formulation}

The number of instructions per user per second for AMF and SMF for each procedure is calculated using the following formula:

\[ \text{Equation 11-1} \quad \text{Nb}_{\text{Inst}}_{\text{NF/proc}} = \text{Nb}_{\text{Inst}}_{\text{proc}} \times \text{Frequency}_{\text{user/s}} \times (\text{Nb}_{\text{Msg}}_{\text{proc}} \times \text{Correction}_{\text{factor}}) \]

The number of CPU core required to run the total instructions per procedure per network function (AMF or SMF) is calculated via the formula below:

\textsuperscript{12} Service request:
- UE Triggered Service Request is considered.
- For this procedure, the impacted SMF and UPF are all under control of the PLMN serving the UE, e.g. in Home Routed roaming case the SMF and UPF in HPLMN are not involved.
- We assume that the Service Request was sent integrity protected.
- The UE identifies List of PDU Sessions To Be Activated in the Service Request message
- We assume that PDU Session ID corresponds to a LADN and the SMF determines that the UE is within the area of availability of the LADN
- We assume that the SMF accepts the activation of UP connection and continue using the current UPF(s);
- No N4 Session Modification is established
- No dynamic PCC is deployed

\textsuperscript{13} Service release request:
- Service release procedure corresponds to AN Release in 5G CP procedures.
- We assume that 3 PDU sessions were active at the time of initiating this procedure. This assumption is based on the fact that each network slice will be served with a separate PDU session. Thus, assuming two different slices with a PDU session for each of them and w third session for the normal calls and chat. Since we do not have a good reference that strengthens this assumption a sensitivity analysis on this is elaborated. Results demonstrates the number of active PDU sessions does not significantly affect the required CPU cores for AMF and SMF (see Appendix for more information).
- The procedure is triggered by the User Inactivity.

\textsuperscript{14} X2-based handover:
- it corresponds to Xn based inter NG-RAN handover in 5G CP procedures.
The total CPU cores required for all the procedures per NF is derived using the following formula:

$$N_{\text{CPU}}_{\text{NF/procedure}} = \frac{N_{\text{Inst}}_{\text{NF/procedure}}}{P_{\text{CPU}}}$$

11.5.2 Results of the simulation
We simulated the proposed model for both AMF and SMF and for the two frequencies while varying the number of users. We consider the same CPU power as in [88], one CPU core has the power of $2.845 \times 10^9$ float operations per second. Results of the simulation are presented in the table below:

Table 11-15 Variation of the number of CPU cores required for AMF and SMF in function of the number of users for both frequency 1 and 2

<table>
<thead>
<tr>
<th>Frequency\number of users</th>
<th>Network function</th>
<th>100x10^3</th>
<th>1000x10^3</th>
<th>10000x10^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency 1</td>
<td>AMF</td>
<td>0.4</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>SMF</td>
<td>0.5</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>Frequency 2</td>
<td>AMF</td>
<td>1.23</td>
<td>12.3</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>SMF</td>
<td>1.51</td>
<td>15.1</td>
<td>151</td>
</tr>
<tr>
<td>Average of frequencies</td>
<td>AMF</td>
<td>0.82</td>
<td>8.2</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>SMF</td>
<td>1</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

Results for frequency 1 are very different from those of frequency 2. To solve this issue, we take the average of frequency 1 and 2 (see third row in the table above). Hence, only one core is needed to serve 100k users for both AMF and SMF and 5 cores are needed to serve 1 million users.

We can conclude from Table 11-15 that both the number of CPU cores needed for AMF and SMF scales linearly with the number of users:

$$N_{\text{CPU}}_{\text{AMF}} = 8.2 \times 10^{-4} \times N_{\text{users}}$$

$$N_{\text{CPU}}_{\text{SMF}} = 10 \times 10^{-4} \times N_{\text{users}}$$

11.6 Cost allocation from a telco operator point of view
In this approach, we adopt the Public cloud cost model, where applications (VNFs) are moved out of on-premise data centers in a bid to decrease costs and increase agility.

Infrastructure as a Service (IaaS) is a model where a third-party provider hosts and maintains core infrastructure, including hardware, software, servers and storage on behalf of a customer. This typically includes the hosting of applications in a highly scalable environment, where customers are only charged for the infrastructure they use [90]. The IaaS market is worth a total of $23.6 billion in 2017, up from $18.2 billion in 2016 [91]. IaaS builds on a
sophisticated distributed data center model combining on-demand/dedicated resources and pay-per-usage made available by IaaS providers. All of them provide flexible compute, storage and networking, self-service and instant provisioning, auto-scaling, security, compliance and identity management features. For our project, Software as a Service (SaaS) and other XaaS providers may also be considered for serverless services to run containers that are becoming more and more present... Amazon EC2, Microsoft Azure and Google Cloud are well-known examples of public cloud providers, while Alibaba Cloud was launched in August 2018.

Leveraging the massive cost benefits of the data center innovations brought by modern virtualization layers, those providers achieve affordable dynamic resources and huge scalability. Each data center runs numerous (tens of thousands) of similar servers, and many (similar) data centers are distributed across the planet, all linked together with high speed links. All physical resources are hidden behind a virtualization screen giving the feeling of an almost unlimited scalability. It allows a customer to receive, for example to run a VNF, a compute node in a question of seconds (online billing), without knowing what its resource’s geographical location is actually - "in the cloud". The customer compute node benefits from the virtualization extensibility characteristics to be sized up/down depending on the processing need, this being achieved in real-time. Furthermore, if the actual physical server behind the compute node is overloaded, technologies such as OpenStack extends the compute node concept that consolidates multiple servers. A virtual server actually made of multiple physical servers is therefore made available to the operator which is free to deploy any number of VNF until the resources are exhausted. More compute nodes can be added on the fly to increase the virtual server size (up to hundreds of cores and TB RAM). The customer benefits of a pay as you grow model directly aligned with its actual revenue. The virtualization platform manages the load to make sure no VNF actually runs across multiple physical servers.

This applies directly to slice-specific VNFs that will leverage the full flexibility of the virtualization concepts: each VNF is optimized in real-time to the exact amount of resources required to achieve its contract. As a consequence, the service operator is billed monthly for the actual resource-hour used and can therefore bill its own customers for their actual usage.

Prices have continuously decreased since 2006 but stay structurally complex. This is the reason the main IaaS providers feature online price calculators. Based on the three VM classes considered above, market prices per hour are shown in Table 11-16.

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>1</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>RAM</td>
<td>8 GB</td>
<td>16 GB</td>
<td>40 GB</td>
</tr>
<tr>
<td>Storage</td>
<td>50 GB</td>
<td>100 GB</td>
<td>1500 GB</td>
</tr>
<tr>
<td>Average public price</td>
<td>~0.1€/hour</td>
<td>~0.4€/hour</td>
<td>~0.6€/hour</td>
</tr>
</tbody>
</table>

Slices being dedicated to specific use cases such as mMTC and URLLC, etc., are delivered by an independent set of logical, i.e. VM, network functions that support the requirements of the particular use case. Each set will be optimized to provide the resources and network topology for the specific service and traffic that will use the slice.
Functions such as speed, capacity, connectivity and coverage will be allocated to meet the particular demands of each use case.

Some operators may consider that, due to the strong requirements (low latency, high reliability, etc) from the 5G use cases, the functional components should not be shared across network slices. This lowers the risk of unwanted side-effects when introducing and running new services and improves security since a cyber-attack breaches one slice the attack is contained and not able to spread beyond that slice.

But the IaaS model actually allows those functional components to be shared across slices - as long as no slice can interfere with the traffic in another slice. If this is achieved preserving the user experience of the network slice to be the same as if it was a physically separate network, sharing the IaaS between slices would further optimize the cost.

### 11.7 Inputs of the cost model of the NFV-based core network:

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade server price</td>
<td>1300</td>
<td>Average price in the internet</td>
</tr>
<tr>
<td>Number of servers</td>
<td>8</td>
<td>We only need 4 but 8 in total for redundancy purposes</td>
</tr>
<tr>
<td>CAPEX Data Center</td>
<td>12753</td>
<td></td>
</tr>
<tr>
<td>Air conditioning</td>
<td>500</td>
<td>[79]</td>
</tr>
<tr>
<td>Installation</td>
<td>1912.95</td>
<td></td>
</tr>
<tr>
<td>Maintenance*5 year</td>
<td>6376.5</td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td>240</td>
<td>Power consumption per server per year in kWh: from the datasheet</td>
</tr>
<tr>
<td>Electricity price kwh</td>
<td>0.014</td>
<td>[76]</td>
</tr>
<tr>
<td>cost power consumption</td>
<td>134.4</td>
<td></td>
</tr>
<tr>
<td>VNF license cost (Dollar/vCPU): 100</td>
<td>25200</td>
<td>[92]</td>
</tr>
<tr>
<td>Nokia router 7750 from BT</td>
<td>1,853</td>
<td>[55] 20383 euro for 11 small sites (like our scenario site)</td>
</tr>
<tr>
<td>Total CAPEX</td>
<td>14,666</td>
<td></td>
</tr>
<tr>
<td>Total OPEX</td>
<td>31,711</td>
<td></td>
</tr>
<tr>
<td>Overhead costs</td>
<td>9275.37</td>
<td></td>
</tr>
<tr>
<td>TCO</td>
<td>55652.22</td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Value</td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>Total traffic (Mbps)</td>
<td>2700</td>
<td></td>
</tr>
</tbody>
</table>