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Towards 5G: Techno-economic analysis of suitable use cases

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ABSTRACT
The evolution of mobile networks towards the Fifth Generation (5G) introduces many concerns from the technical and economic points of view. Expected new applications exceed mobile networks' current capabilities, and 4G networks will have to evolve into 5G networks to provide some with a proper service. With regard to the ambitious intended performance of 5G networks, a huge process is required which will need to be faced up to both technically and economically. The 5G "ready system" standard is scheduled for 2020. However, only a few studies have carried out techno-economic evaluation of 5G. This paper presents a techno-economic analysis to foresee some feasible technical architectures leading to suitable and affordable use cases. The paper presents a new approach based on different evolving technical scenarios, establishing combined 4G/5G technical solutions and a roadmap that could provide useful insights about the most suitable use cases by scenario. Moreover, it analyses these possible use cases to determine their feasibility by optimizing their deployment costs. The study is based on the standardization process, integration of different views of key industrial players and mathematical modelling to address the new applications that 5G will provide. Finally, conclusions are drawn from the analysis and a recommendation score is established, providing useful advice to support the strategic decisions of the different stakeholders, technologists and investors involved in deployment of 5G networks.

Key words: 5G, techno-economic analysis, use cases, deployment, recommendation score

1. Introduction

The non-availability of complete 5G standards and the lack of a closed technical definition have provoked a clear shortage of 5G research combining technological and economic implications [10]. Particularly, few papers discuss the economic impact of specific technologies potentially involved in 5G deployments: [15] studies the techno-economic aspects of ultra-dense femtocell-based deployment and distributed antenna systems technology, [17] analyses several solutions of optical fiber based 5G back/fronthaul, [33] provides tools for selecting the most appropriate radio access technologies (RAT) in future 5G network ecosystems, [37] proposes a techno-economic analysis approach for upgrading 4G to 5G and points out that the reuse of existing sites could have a large impact on reducing costs, and [19] includes a complex and detailed analysis of 5G network deployment in Britain for the period 2020–2030, developing several spatial and temporal rollout scenarios. In contrast, the literature is rich in techno-economic studies for previous wireless networks (i.e., 3G or wireless local access) [22], [24], [31]. Therefore, it is worth studying the new mobile generation with this proposed approach.
In this context, this paper is focused on the achievability of 5G goals during the transition between fourth and fifth generations, where many uncertainties remain, especially in 5G definition and standardization [2] [3]. In this context, we propose a phased roadmap approach combining feasible deployment scenarios and high-level 5G evolving architectures, assuming that 5G standards will be fully completed by the end of 2020. We analyze their achievability in the evolution towards 2020 alongside deployment costs in each scenario.
This paper helps to fill this gap observed in the research by focusing on one of the key issues to be addressed, both technically and economically: transition between 4G and 5G. It proposes a system-level approach based on the definition of different technically evolving scenarios which combine network elements from 4G and 5G networks, and it defines a roadmap that could provide useful insights about the most suitable use cases by scenario. We also propose a basic mathematical model to evaluate the feasibility of these use cases by optimizing their deployment costs. Furthermore, we provide a basic overview for operators to decide in the initial stage whether or not to invest, and where to do so, according to the timeframe and the potential demand associated with the use cases. This is achieved by defining and calculating some basic indicators and mathematically optimized scores, which provide an initial orientation of the best possible use cases to implement.
Following this introduction, the paper is organized into three main sections. Section 2, 5G state of the art, addresses the different key topics for 5G and its current state: spectrum regulation, standardization and technological state-of-the-art. Each area provides some assumptions to be considered when making the analysis. The next section is devoted to the techno-economic analysis, explaining the methodology proposed and how the analysis is carried out. Moreover, a sensitivity analysis is included in this section. Finally, the last sections, 4 and 5, are the results discussion and conclusions, establishing recommendations for the main techno-economic path in the evolution towards 5G.

2. 5G state of the art

2.1 Standardization and spectrum issues

Several aspects of Fifth Generation (5G) mobile communications are already established. Initially, 5G networks will comprise both enhanced Long Term Evolution systems (LTE-A Pro) and new deployed 5G systems, New Radio (NR) and Next Generation Core (NGC). These two systems will work together to address the wide variety of 5G use cases optimally, but it is still unclear how this combination will be achieved. Secondly, the International Telecommunication Union Focus Group for International Mobile Telecommunications (IMT) by 2020 (ITU FG IMT-2020), [25], has defined a plan called IMT-2020, whose aim is to define the common objectives that 5G networks should fulfil in terms of parameters such as peak data rate and mobility. Each of these parameters is assigned a target value, called Key Performance Indicator (KPI). Comparison of KPIs between stages is one of the vertebrae of the technical analysis in this article, and the eight 5G goals and KPIs per stage are included in Table 1.
Furthermore, 3GPP froze Release 14, which introduced important concepts such as the Massive Internet of Things (MIoT) and Mission Critical Services (MCS) over LTE, in June 2017, [4]. It has also approved completion of the standalone Release 15, [2], and is now concentrating on Release 16 "5G phase 2" [3]. The two pending releases both address big issues such as NR architecture and forward compatibility between LTE-A and NR, according to [9].

Table 1. IMT-2020 and IMT-Advanced KPI values related to LTE (prepared by the authors based on [39])

Parameter VS System improvement	Peak Data Rate (Gbps)	Edge Throughput (Mbps)	Spectrum Efficiency (times x)	Mobility (km/h)	Latency (ms)	Connection Density (devs/km^2)	Network Efficiency (times x)	Area Traffic Capability (Mbits/s/m^2)
LTE (R8)	0.3	6	1x	100	100	1.2 x 10^4	0.11x	0.1
LTE-A (R10 and beyond)	1	10	1x	350	10	10^5	1x	0.1
LTE-A Improvement	*3.33x*	*1.66x*	*1x*	*3.5x*	*10x*	*5x*	*1x*	*1x*
IMT-2020 (R15/5G)	20	100	3x	500	1	10^6	100x	10
IMT-2020 Improvement	*66x*	*16.6x*	*3x*	*5x*	*100x*	*50x*	*100x*	*100x*
LTE-A IMT-2020 Improvement	*20x*	*10x*	*3x*	*1.4825x*	*10x*	*10x*	*100x*	*100x*

2.2 Technology: Radio and Core Innovations

LTE has evolved into LTE-Advanced, and will be enhanced into LTE-Advanced Pro. This enhancement will constitute the first stage in the transition to 5G and the main scenario is that a 5G network will consist of LTE-A Pro networks and 5G networks (each with its NGC and NR), which will interwork. This means that current LTE architecture segments will be the same or quite similar for 5G networks: the Radio Access Network (RAN) with its evolved NodesB (eNBs) and the core network with all its modules. Tight interworking of an evolved LTE (targeting spectrum below 6 GHz) with NR (targeting spectrum below and especially above 6 GHz) will provide different functionalities after WRC-19. In this regard, NR will not be fully deployed before WRC-19, when this new targeted spectrum will be better analyzed. Moreover, 5G will require a paradigm shift that includes very high carrier frequency spectra with massive bandwidths, LTE-NR/Wi-Fi interworking, [7], extreme base station densities and new femtocells, [30], and unprecedented numbers of antennas to support the enormous increase in the volume of traffic, [11-12]. Finally, RAN architecture must evolve towards a flexible radio access network. This flexibility will be achieved in two steps, from a Distributed RAN (D-RAN) towards a Centralized RAN (C-RAN), also called Cloud C-RAN [20].
Regarding core, the Evolved Packet Core (EPC) that provides converged voice and data services on LTE networks will be sufficient to cover the initial less demanding services, and it will also be enhanced, so service providers will use a common physical infrastructure, avoiding deployment of parallel physical networks [18].
One of the most ambitious goals for the entire network is network slicing. This consists of separating functionalities that can work independently into different slices, [35]. Slicing will enable the possibility of deploying not all the core or RAN, but just a part made up of the desired slices, reducing CAPEX and OPEX [14]. Related to network slicing and independent scalability, control and user plane separation will be of great importance in a 5G network. In this sense, the expected strategy will consist of deploying a central node to carry out all the control operations to easy management tasks, and using distributed closer-to-user nodes to carry out data plane functionalities to improve data rates.
Finally, there are two technologies which will be fundamental to ensure flexible, leaner networks, and cost saving. They relate to the increasing importance of the cloud, not only for storage but also for computing, and comprise software, infrastructure and platform services [23] and reduce cost by almost 60-70% [32], [16]:
1) Software Defined Networks (SDN), which follow three principles: separation of control and forwarding functions, control centralization and ability to program networks' behavior by using well-defined interfaces, [28].

2) Network Function Virtualization (NFV), which consists of implementing some specific functions in software rather than in hardware at the operator's will. This will increase power efficiency and bring cost reductions, [27].

3. Techno-economic analysis and results

3.1 Methodology of analysis

In this section we carry out the technical and economic analysis, firstly by introducing feasible evolving scenarios; secondly by establishing network element combinations that could provide useful insights about the most suitable use cases, and then by analyzing these possible use cases to determine their affordability by optimizing their deployment costs. Finally, we will discuss and extract conclusions from these quantitative results and evaluate their techno-economic impacts. Particularly, for the technical analysis, the initial goal will be to measure the technical capabilities in each possible feasible combination, while for the economic analysis, the variable to evaluate will be deployment costs. Here, the method of analysis consists of two distinct phases: the technical analysis and the economic analysis based on the technical solution. The discussion and conclusions cover both phases.
The technical analysis comprises different steps:

1) Selection of possible technical scenarios in accordance with the standardization process,
2) Matching of scenarios with possible use cases,
3) Evaluation of the solutions through definition and measurement of an indicator, hereinafter called Technical Rate (TR) and defined in section 3.2.3.

After these steps, the economic analysis comprises:

1) Cost analysis,
2) Optimization of the cost recommended solution,
3) Study of total costs, the previous results being based on cost per user.

All these study processes are described in detail in the following sections.

3.2 Technical analysis

3.2.1 Cases of use analysis

The cases of use have been extracted from ITU's reports [25-26], being understood to be sufficiently standardized. As can be observed, there are three cases of use comprising most applications[1]. They are:

- Enhanced Mobile Broadband (eMBB), which includes some services like Virtual & Augmented Reality, 3D streaming as well as enhanced previous applications such as voice traffic and augmented edge throughput in small and big cells.
- Massive Internet of Things (MIoT) to address machine-to-machine (M2M) communications. MIoT traffic will be flexible to errors and delays, since its information will not generally have very high priority. Release 13 already standardized an initial protocol, Narrow Band IoT (NB-IoT), which has proven to be a valid solution for many applications within MIoT, [28].
- Mission Critical Service (MCS): comprising applications such as autonomous (self-driven) cars which will need to have almost no delay or errors due to their real-time requirements.

3.2.2 Scenario selection and binding with IMT-Stages

From the first section on 5G state of the art, we can establish the following main scenarios:

1) Scenario A: the first feasible scenario is based on legacy mobile networks, from enhanced LTE networks (i.e. LTE-A Pro systems). It will consist of enhanced RAN and EPC that will be sufficient to cover the less demanding applications 5G will provide.

2) Scenario B: this is an intermediate scenario. There are many deployment options for 5G combining old and/or new RAN and core segments. From all the options listed in [38], there are three which have at least one of the subsystems deployed while the other one is still being developed. Additionally, the core network will be less sensitive to the deployment process because of the flexibility provided by software technology such as NFV and SDN. Therefore, for the intermediate scenario, we assume that EPC will have already been deployed, as indicated in section 2.2, so core costs will be basically related to deploying the NGC. NR will be partially deployed (which is possible due to slicing), while it will be possible for LTE RAN to be connected to the two deployed cores (both of which will interwork to optimally deal with every case of use).

3) Scenario C: the last deployment scenario must necessarily consist of the NR interworking with the legacy RATs, [31], and the Next Generation Core Network (NGCN) interworking with the EPC (scenario B).

[1] In addition to these three use cases analyzed, others should at least be mentioned, all belonging to a vertical market which will be enabled by the power of 5G [5]: Connected Vehicles, Enhanced Multimedia and Fixed Wireless Access.

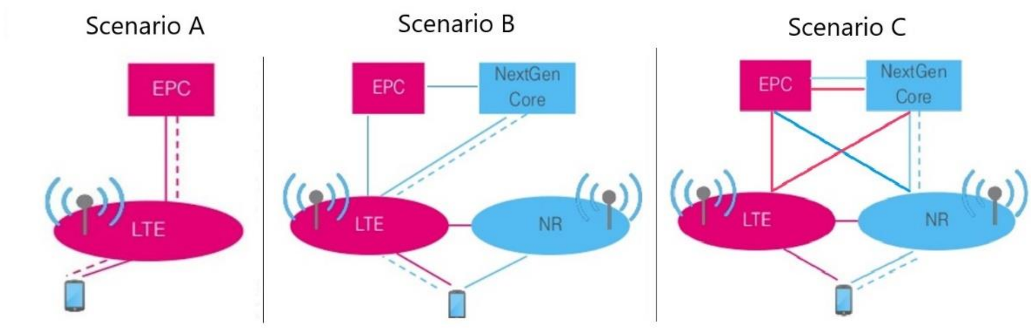


Fig. 1 Deployment Scenarios: Scenario A, based on LTE-A Pro networks; Scenario B, intermediate scenario; Scenario C, IMT-2020 compliant

Figures 1 shows the selected deployment scenarios, named A, B and C, respectively. These 3 scenarios follow a chronological path. As IMT-Advanced is expected to be concluded in 2018/2019, it can be said that the first network architectures to fulfil IMT-Advanced requirements will consist of LTE-A Pro networks (scenario A). On the other hand, IMT-2020 will be fulfilled last, by scenario C, which includes the new core and new radio belonging to future 5G networks, [8]. In between, scenario B must be placed somewhere between scenarios A and B [36]. Assuming that bands over 6 GHz will not be standardized, only part of the NR will be ready to be deployed, therefore, scenario B will be ready to be deployed during 2019 while scenario A could be deployed before since end of 2018 (Figure 2). Because of standardization and development uncertainties, we will take a possible offset for each scenario into account. This offset will consist of delaying deployment of our selected scenarios A, B and C by 6 months and can be explained in two ways: First, because operators are not willing to transact to the next generation without amortizing LTE systems, assuming the investment made on these systems. Secondly, because once the different releases are terminated, it will take some time for the different players to implement them. Hence, Figure 2 shows the binding between IMT-Stages and the time interval each scenario comprises.

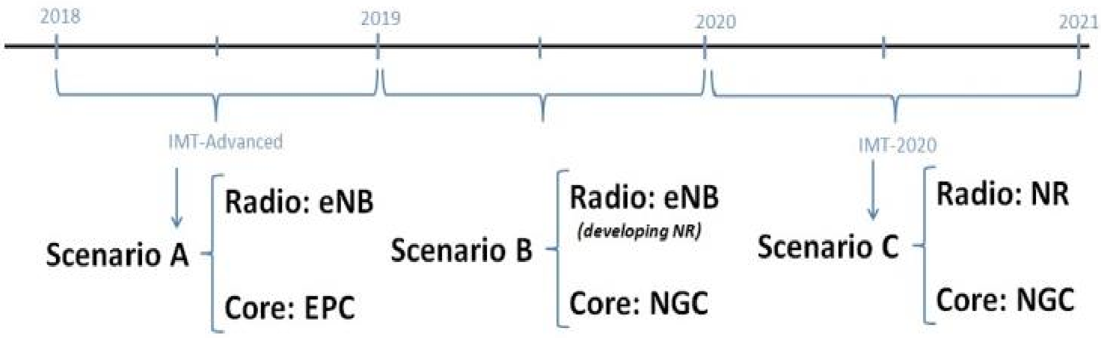


Fig 2. IMT planning alongside scenarios timeline

3.2.3 Technical Rate definition and evaluation

This section's objective is to analyze the influence of every KPI in each case of use. Moreover, we are going to calculate the improvement ratio for every KPI between the three stages. In order to do that, we define the TR which is intended to represent the technical improvement in the transition between two scenarios, the LTE, Release 8, and the selected scenario from A, B and C (Release 10 and beyond) for a specific case.

The TR is a weighted and normalized summation calculated for each combination of scenario (Table 1) and case of use (Table 2). On the one hand, Table 1 shows the value of every KPI (e.g. Latency, Mobility) by stage (current LTE-legacy, IMT-Advanced and IMT-2020), [26]. On the other, Table 2 shows the KPI importance per parameter in each case of use (EMBB, MIoT, MCS) divided into 3 levels. These levels will be categorized from 1 to 3, also according to ITU in [26], where 1 means the lowest importance.

Table 2. IMT requirements classified by case of use parameters and their importance. Reconstructed from ITU, (2015)

Use Case	Peak Data Rate	Edge Throughput	Spectrum Efficiency	Mobility	Latency	Connection Density	Network Efficiency	Area Traffic Capability	Average

EMBB	3	3	3	3	2	2	3	3	2.75
MIoT	1	1	1	1	1	3	1	1	1.25
MCS	1	1	1	3	3	1	1	1	1.5

The TR expression is given in (1),

$$TR_{Scenario\ i}^{Case\ of\ use\ j} = \frac{\sum_{l=1}^{8} W_i^{KPI\ l} \times Improvement_i^{KPI\ l}}{24} \quad (1)$$

where i represents each scenario A, B or C; $W_i^{KPI\ l}$ is the ranking value, from 1 to 3, for the importance of every KPI in each case of use, as defined in Table 2, and $Improvement_i^{KPI\ l}$ is the improvement rate (number of times better) of each KPI compared between the two scenarios, LTE compared to A, B or C (lines in italics in Table 1). The TR gives an indication of how well a scenario works comparatively for a case of use; it does not have units and is normalized (8 is the number of parameters considered and 3 the maximum ranking value). This definition is purely technical and provides a basic general indication, independently of specific deployment conditions (e.g., country or geography).
The next step is to calculate the TR of each scenario from (1). Scenarios A and C can be calculated directly. However, the intermediate state, scenario B, is not exactly equidistant from scenarios A and C, as NGC will be already deployed, and NR will be under development. Hence, assuming TR_{SA} and TR_{SC}, the task is to determine TR_{SB}. We assume that scenario B represents a slightly more advanced point that the mid-point between scenarios A and C. At this point, we consider two alternatives:

a. Assuming that technical performance depends equally on the core and the network, it may be supposed that:

$$TR_{SB-O} = \frac{TR_{SA} + TR_{SC}}{2} + \frac{\left(\frac{TR_{SA}+TR_{SC}}{2}\right)}{2} = 3x\ \frac{TR_{SA}+TR_{SC}}{4} \quad (2)$$

This equation represents approximately "three quarters" of the network being deployed (enhanced core, enhanced RAN and NGC).

b. Assuming in a pessimistic scenario that RAN has more influence on the technical performance, which seems reasonable for some KPIs like Peak Data Rate, Spectrum Efficiency, Latency or Edge Throughput, [13], TR_{SB} must comply with the following inequality: $TR_{SA} < TR_{SB} < 3x\ \frac{TR_{SA}+TR_{SC}}{4}$. It seems reasonable to set a correlation such that the technical performance depends 65% on the RAN and 35% on the core:

$$TR_{SB} = 0.65 \times TR_{RAN-SB} + 0.35 \times TR_{core-SB} \quad (3)$$

Where the following are known:

$$TR_{RAN-SB} = 0.75 \times TR_{RAN-SC} \quad (4)$$

$$TR_{core-SB} = 1 \times TR_{core-SC} \quad (5)$$

By weighting in the formula for each side, the new TR_{SB} is defined like this:

$$TR_{SB-P} = \left(\frac{0.65 \times 0.75 + 0.35}{2}\right) \times (TR_{SA} + TR_{SC})$$

$$= 0.41875 \times (TR_{SA} + TR_{SC}) \quad (6)$$

Therefore, we have two technical rates for scenario B: TR_{SB-O} & TR_{SB-P}, representing optimistic and pessimistic situations respectively. This will provide two possibilities for the intermediate scenario which will converge into one final scenario. To guarantee the robustness of the TR_{SB} calculation, a sensitivity analysis of this intermediate scenario, and how much the TR_{SB} value contributes to the output uncertainty, is discussed in section 4.1. Table 3 shows the resulting technical rates (TR) by case of use and scenario.

Table 3. Technical rate correlations with scenarios and cases of use

Technical Rate (TR)	Scenario A	Scenario B-Opt.	Scenario B-Pess.	Scenario C
EMBB	2.63	38.63	21.57	48.825
MIoT	1.52	18.03	10.06	22.525
MCS	2.22	22	12.28	27.1083

At this point, some findings must be highlighted:

1) The lower TRs in earlier scenarios may be misleading, as TR is only a measure of the technical performance. They do not mean that the use case requirements could be fully achieved. For example, MCS applications and use cases will not be achievable in scenario A, because of the high latency and low data rate given by eNodeBs.

2) There are around 20 identified use cases for IMT. This means that some of them are among the three big categories studied. So this approach will not always reflect the reality of all of them. This is the reason why EMBB has the highest technical rate, over two times more than the next case of use: there are a lot of KPIs that must be enhanced. Therefore, it will be more expensive (in terms of this kind of TR-related costs) to achieve it in any scenario.

Which use cases should be provided in each scenario in order to find the best compromise between cost and achievement of every case of use can now be discussed. The results are shown in the graph in Figure 3, including two temporal possibilities for each of the three use cases depending on the fulfillment of the expected deployment dates (on-time, or with a time delay of six months, in a conservative calculation). For each of the three identified use cases, there is a solid line representing the optimistic assumptions evaluation and a dashed line representing the pessimistic one. The slope of each line shows the increase in the technical rate for a given case of use related to the comparison between the different scenarios, i.e., from scenario A to scenario B, the greater the slope, the greater the improvement.

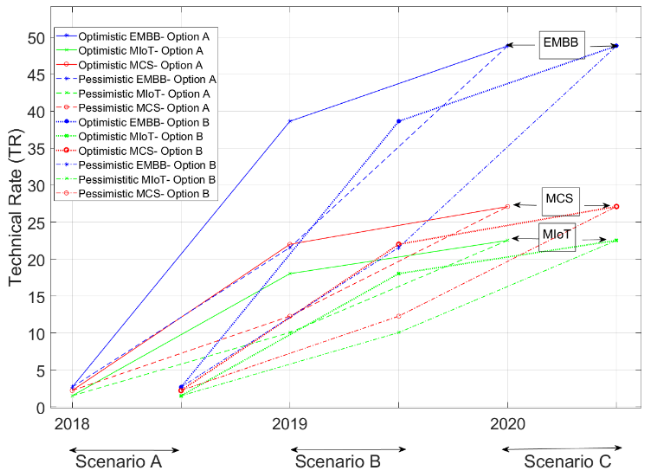


Fig 3. Technical rate correlations among scenarios and cases of use

As can be observed qualitatively, MIoT is the one that increases its TR less (lowest slope) in the second transaction, from scenario B to C. Secondly, to analyze the evolution of the TRs, we calculate a matrix which shows the improvement between scenarios: the number of times TR_{Si} is better than TR_{Sj} (previous scenario on the left, next on the right). This quotient will be named Technical Rate Correlation (TRC) and defined as:

$$TRC_{Si-Sj} = \frac{TR_{Si}}{TR_{Sj}} > 1 \qquad (7)$$

Again, it must be noted that as there are two possible options for Scenario B, there will be two $TRC_{SA\text{-}SB}$ and another two $TRC_{SB\text{-}SC}$. As can be seen from Table 4, EMBB is the case of use that improves most in both transitions between scenarios. Then, MIoT improves more than MCS in technical terms.

Table 4. Technical Rate (TR) correlations with scenarios (SA, SB, SC) and cases of use

Technical Rate Correlation (TRC)	$TRC_{SA\text{-}SB}$ Optimistic	$TRC_{SA\text{-}SB}$ Pessimistic	$TRC_{SB\text{-}SC}$ Optimistic	$TRC_{SB\text{-}SC}$ Pessimistic	$TRC_{SA\text{-}SC}$ (total)
EMBB	14.38x	8.029x	1.263x	2.263x	18.1759x
MIoT	11.86x	6.62x	1.249x	2.238x	14.815x
MCS	9.87x	5.512x	1.232x	2.206x	12.163x

The final step is to discuss whether each of the use cases could work properly in each scenario. It may seem obvious that the three cases of use may be developed in parallel. However, the aim is to find the optimum combination of resources and time to set an order of deployment. There are some extra conditions and assumptions to be considered, according to ITU in 2016, [26]:

1) EMBB is the one which includes the most varied cases of use. That is why so many KPIs, many of which will increase by up to 100 times compared to current LTE networks, are so important. This does not mean that some of the cases of use within EMBB (such as enhanced voice/video calls) would be feasible in the early stages including scenario A and B.

2) For MIoT, the new core would be already developed by this time, while NR would be under development. This result is logical because the KPIs with less weight for MIoT are related with peak data rate, throughput, etc., most of

which depend on the RAN. Even with this conclusion, NB-IoT (already being standardized) has proved to be a valid solution, [26].

3) The results obtained for MCS may be surprising. While the improvement rate for MCS is less than for MIoT, it can be found that MCS's slope is steeper, which means that it gradually improves more than MIoT but its TR was initially smaller. This suggests it would be better to wait until deployment of scenario B.

3.3 Economic analysis: deployment costs

As a starting point, we take the cost statement from the report "Identification and quantification of key socio-economic data to support strategic planning for the introduction of 5G in Europe" according to [13]. This report estimates the deployment costs of 5G by extrapolating the currently available data from other generations using a linear regression from the known cost of previous generations. Table 5, taken from [39], shows the evolution of costs.

Table 5. 5G deployment cost estimation.

YEAR	1991 (2G)	1995	2000	2001 (3G)	2005	2010	2014 (4G)	2015	2020 (5G)
Deployment Cost (€/subscriber)	116	119	123	123	128	132	135	136	140

For some scenarios, these costs will not be actual deployment but deployed equipment enhancement costs. A deployment cost can be associated with each scenario, as shown in Table 6.

Table 6. Breakdown and cost analysis of scenario architectures

	Scenario A-2018	Scenario B-2019	Scenario C-2020
Core	EPC	NEW (NGC) & LTE	NEW (NGC)
RAN	LTE	Developing NEW (NR)	NEW (NR) Assisted: EPC
Costs (€/subscriber)	138.875	139.75	141
Increase over 4G (LTE: 135 €/subscriber)	1.0287	1.0351	1.0444

The costs per subscriber have been calculated from the initial data in Table 5, [37], by finding

$$m = \frac{\Delta y}{\Delta x} = \frac{136-119}{2015-1995} = 0.85 \; \& \; b = 110 \qquad (8)$$

and substituting these values in a linear equation y=mx+b. For each network's segment, there are two types of costs to analyze: Enhancing Costs (EC) and Deployment Costs (DC). Furthermore, for each scenario, the total deployment costs can be described as:

$$Cost_{Scenario\ i} = Cost_{RAN} + Cost_{CORE} \qquad (9)$$

Where any costs can be either DC or EC. Considering the Table 6 breakdown and Table 5 costs per subscriber, we can formulate the corresponding equation for each scenario.

$$\text{Scenario A} \rightarrow EC_{core} + EC_{RAN} = 138.875 \qquad (10)$$

$$\text{Scenario B} \rightarrow DC_{core} + (\varepsilon \times EC_{RAN} + (1\text{-}\varepsilon) \times DC_{RAN}) =$$

$$= 139.75 \qquad (11)$$

$$\text{Scenario C} \rightarrow DC_{core} + DC_{RAN} = 141 \qquad (12)$$

Regarding the cost of the different subsystems: information from Costanzo [18], and several leading equipment providers has shown that due to the new techniques such as SDN and NFV on which the Cloud-Core will depend, the NGCN's cost can be assumed to be very similar to that of the enhanced EPC. Hence, the costs for the new core will mainly include SW engineering and programming, creation of cloud data centers and virtualization tasks.

The assumption can be easily explained therefore by stating that $EC_{core} = \mu \times DC_{core}$. Here, μ represents a factor very slightly smaller than 1, which reflects the fact that deploying a new core will always be more expensive than enhancing the old one, even if their cost is similar. It will be used in the optimization process to set a boundary condition declaring that DC_{core} must be greater than EC_{core}. This leads to a value of μ less than 1. However, in line with the previous paragraph and with [18], it should be approximately 1. With these assumptions, the new system can be expressed as follows:

$$\text{Scenario A} \rightarrow \ \mu \times DC_{core} + EC_{RAN} = 138.875 \quad (13)$$

$$\text{Scenario B} \rightarrow DC_{core} + (\varepsilon \times EC_{RAN} + (1\text{-}\varepsilon) \times DC_{RAN}) =$$

$$= 139.75 \quad (14)$$

$$Scenario\ C \rightarrow DC_{core} + DC_{RAN} = 141 \quad (15)$$

Where parameter ε represents the costs related to the RAN in Scenario B. In this case, ε splits the costs associated with the RAN between the cost of enhancing it and the cost of deploying it. A sensitivity analysis with ε for scenario B is also performed in in section 4.1. The main difference from μ is that this parameter allows the best expenditure option to be decided upon. This means that when the effect of the constraint (money spent on enhancing the RAN) is known, the amount of money spent on enhancing and deploying can be optimized.

3.3.1 Optimizing the solution

This optimization problem has 6 variables, all the kinds of costs plus variables μ and ε, and an objective function to minimize/optimize:

$$f(EC_{Core}, EC_{RAN}, DC_{core}, DC_{RAN}) = EC_{Core} + EC_{RAN} + DC_{core} + DC_{RAN} \quad (16)$$

Furthermore, it has 3 conditions corresponding to the three scenarios proposed and some lower and upper bounds for the variables which can be summarized as:

$$EC_{Core}, EC_{RAN}, DC_{core}, DC_{RAN} > 0$$
$$DC > EC$$
$$0.5 < \varepsilon < 1$$
$$0 < \mu < 1$$

The first condition explains that costs associated with the deployment of 5G must be larger than those associated with enhancing 4G networks. The second states that ε, whose range should be from 0 to 1, must be greater than 0.5. This means that in Scenario B more than the half of the investment associated with the RAN will be dedicated to enhance LTE RAN. So more money will be invested in enhancing the RAN rather than deploying the new one. Last, the third condition states numerically that deploying the new core will be more expensive that enhancing the old one, as well. With this input data, we solve the optimization problem with a Matlab script, using the 'interior-point' one algorithm, and fminimax (find the optimal value that minimizes the maximum cost to pay) and fmincon (find the minimum possible cost) functions. Table 7 summarizes the results obtained:

Table 7. Comparison of variables between functions

	f_{mincon}	$f_{minimax}$
EC_{core}	70.22	67.96
EC_{RAN}	68.66	70.91
DC_{core}	70.88	68.42
DC_{RAN}	70.12	72.58
ε	0.85	0.75
μ	0.99	0.99
f	279.875	279.875

Relevant findings are:

1) The problem converges and has a finite solution, which is obviously the sum of the costs of Scenarios A & C, which were respectively the sum of the enhancing and deployment costs.

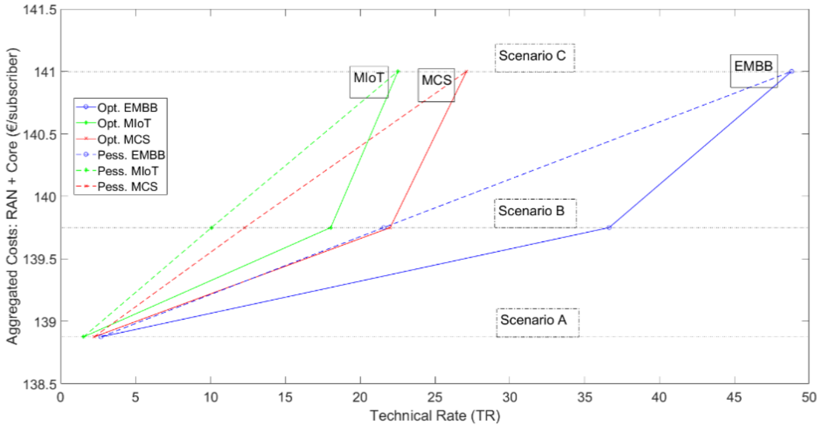
2) Parameter μ remains constant and almost equals 1. This confirms the opinion given by several experts, from vendors of mobile infrastructure worldwide, on the similar price between enhancing the EPC and deploying the NGCN.

3) Parameter ε varies but is always above 0.75. In the highest case, it equals to 0.85, what would mean that the investment costs on the RAN would optimally incur in an 85% in enhancing it, and only a 15% in deploying the NR (for scenario B). This also supports the previous assumption that stated that the NR could be considered non-deployed.

3.3.2 Analyzing Technical Rate versus deployment costs

To conclude the study, technical and economic data should be matched (TR vs. deployment costs). Figure 4 shows this commitment with the costs displayed as €/subscriber. The greatest improvement appears between scenarios B and C. The eMBB case of use is the one which would improve most, in both relative and absolute terms. The linear growth trend for the pessimistic cases is noteworthy: as the weight for the side which improves most (the core) becomes smaller, the improvement effect is minimized for the first transition. Consequently, in the second transition, where NR is deployed, the increase becomes greater (compared to the optimistic scenario) so that the final TR is reached in both cases. If more weight were given to the Core, the TR of Scenario B would increase.

Fig 4. Total aggregated costs vs. TR for each case of use



Finally, as costs are considered per subscriber (€/subscriber), we should estimate the total number of subscribers to obtain a comprehensive view of costs, in absolute terms. We will calculate them for the European market, using Ericsson's Mobility Report, [21] that reveals trustable data in terms of subscriptions/year (table 8).

Table 8. West Europe subscriptions (millions) & traffic figures. Based on [21]

	2016	2022	CAGR 2016-2022
Mobile	550	580	1%
Smartphone	380	480	5%
Data traffic	2.7	55	40
Total mobile	1.2	10	40%

Now, the different deployment costs for each of the scenarios can be established by multiplying the number of LTE subscribers by the cost per subscriber for each scenario. This is shown in Table 9 and Fig. 5 represents the total deployments costs versus the TR previously calculated.

Table 9. Calculated subscriptions and deployment costs from 2016 to 2020

	2016	2017	2018 (SA)	2019 (SB)	2020 (SC)
Mobile subscriptions (million)	555	560	565	570	575
Smartphone subscriptions (million)	185	260	325	420	455
Costs (€/subscriber)	-	-	138.875	139.75	141
Total costs (billion €)	-	-	45.134	59.695	64.155
Percentage of LTE+5G subscribers	33%	46.43%	57.52	73.68%	79.13%

3.4 Sensitivity analysis

Of the three scenarios analyzed, Scenario A (based on LTE-A Pro networks), Scenario B (the intermediate scenario), and Scenario C (IMT-2020 compliant), the Scenario B is the most uncertain one, but it will most probably be deployed. Its first source of uncertainty is the RAN weight to calculate the TR, displayed in equation (3), and the second source is the parameter ε affecting equation (14), related to the economic impact of its deployment. These two uncertainty

sources are uncorrelated. Both are evaluated below using a sensitivity analysis in a one-at-a-time approach. Such analysis will provide an uncertainty evaluation of the results and test the robustness of the model presented.
The proposed analysis consists of a local method based on partial derivatives. Equation (3) assumed that the RAN would affect the TR by 35%, whilst equation (2) assumed that the RAN and the Core would affect it by 50% each. It may be therefore generalized that:

$$TR_{SB} = [a \times TR_{RAN-SB} + (1-a) \times TR_{core-SB}] \times (TR_{SA} + TR_{SC}) \quad (17)$$

where a is the weight of the RAN to calculate the TR.
Now, the partial derivative of TR_{SB} over the new parameter a is as follows.

$$\frac{\partial TR_{SB}}{\partial a} = [TR_{RAN-SB} - TR_{Core-SB}] \times (TR_{SA} + TR_{SC}) \quad (18)$$

Bearing in mind that $TR_{RAN\text{-}SB}$=0.75 and $TR_{Core\text{-}SB}$=1, which indicate the deployment status for each side of the network, (18) becomes:

$$\frac{\partial TR_{SB}}{\partial a} = -0.25 \times (TR_{SA} + TR_{SC}) \quad (19)$$

TR_{SA} and TR_{SC} can be found from Table 3. Following the definition of sensitivity, this result means that a variation of 1 unit of parameter a (which in this case is the maximum variation since its range is from 0 to 1) would affect in a (negative) variation for the TR_{SB} of -0.25 times the sum of the other two TRs. The calculation is as follows for each of the use cases.

$$\frac{\partial TR_{SB-EMBB}}{\partial a} = [TR_{RAN-SB-EMBB} - TR_{Core-SB-EMBB}] \times (TR_{SA-EMBB} + TR_{SC-EMBB}) = -12.86 \quad (20)$$

$$\frac{\partial TR_{SB-MIoT}}{\partial a} = [TR_{RAN-SB-MIoT} - TR_{Core-SB-MIoT}] \times (TR_{SA-MIoT} + TR_{SC-MIoT}) = -5.943 \quad (21)$$

$$\frac{\partial TR_{SB}}{\partial a} = [TR_{RAN-SB-MCS} - TR_{Core-SB-MCS}] \times (TR_{SA-MCS} + TR_{SC-MCS}) = -7.33 \quad (22)$$

Knowing the sensitivity that matches the maximum deviation (called MD for simplicity) for the range of values of parameter a, the sensitivity analysis is completed by calculating the relative variation with respect to the range of the TR, which gives an indication of how much the worst assumption for parameter a would affect the TR_{SB}:

$$MD_{EMBB} = \left| \frac{\frac{\partial TR_{SB-EMBB}}{\partial a}}{TR_{SC-EMBB} - TR_{SA-EMBB}} \right| = \left| \frac{-12.86}{48.825 - 2.63} \right| = 0.2783 = 27.83\% \quad (23)$$

$$MD_{MIoT} = \left| \frac{\frac{\partial TR_{SB-MIoT}}{\partial a}}{TR_{SC-MIoT} - TR_{SA-MIoT}} \right| = 0.2829 = 28.89\% \quad (24)$$

$$MD_{MCS} = \left| \frac{\frac{\partial TR_{SB-MCS}}{\partial a}}{TR_{SC-MCS} - TR_{SA-MCS}} \right| = 0.2945 = 29.45\% \quad (25)$$

This reflects that choosing a=0 when a=1 is true causes a maximum error of around 30%. However, with the two values that have been actually used in the analysis (a=0.65 and a=0.35), the maximum value will be the difference between a (whichever its value) and its nearest bound, i.e., 0.35. Therefore, the true maximum error will be 0.35 × 0.2945 = 0.1 = 10%.
As for parameter ε, which represents the costs related to the RAN in Scenario B. the same procedure will be followed, but making the derivative in equation (13) with respect to ε as follows:

$$\frac{\partial Scenario_B}{\partial \varepsilon} = EC_{RAN} - DC_{RAN} \quad (26)$$

EC_{RAN} and DC_{RAN} being the enhancing costs and deployment costs of the RAN respectively.
As was calculated and shown in Table 7, there were two values of ε that led to two pairs of values of EC_{RAN}, DC_{RAN} because of the optimization function used in each situation. So, for each function, the derivative and the MD will be different although they have been calculated in the same way. For calculation of the MD, we will assume that, depending on ε value, the error will be weighted by 0.75 and 0.85 respectively. As indicated, the functions fminimax and fmincon represent the optimal value that minimizes the maximum cost to pay and the minimum possible cost respectively. Moreover, the denominator in the following equations will be f, since it represents the cost summation.
For the fmincon function:

$$\frac{\partial Scenario_B}{\partial \varepsilon} = EC_{RAN} - DC_{RAN} = 68.66 - 70.12 = -1.46 \quad (27)$$

$$MD_{\text{fmincon}} = \left| \frac{\frac{\partial Scenario_B}{\partial \varepsilon}}{f} \right| = \left| \frac{-1.46}{279.875} \right| = 5.216 \times 10^{-3} = 0.521\% \quad (28)$$

For the fminimax function:

$$\frac{\partial Scenario_B}{\partial \varepsilon} = EC_{RAN} - DC_{RAN} = 70.91 - 72.58 = -1.67 \quad (29)$$

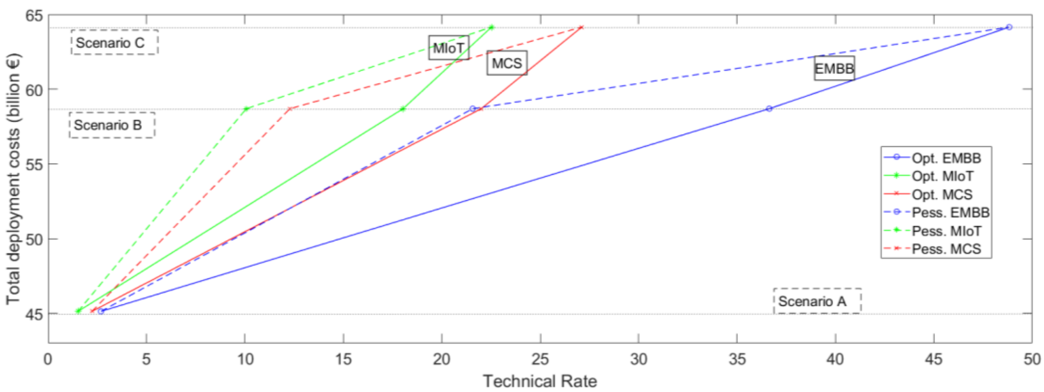
$$MD_{\text{fminimax}} = \left| \frac{\frac{\partial Scenario_B}{\partial \varepsilon}}{f} \right| = \left| \frac{-1.67}{279.875} \right| = 5.967 \times 10^{-3} = 0.597\% \quad (30)$$

Thus, the maximum error will be for the fminimax function, which when weighted is 0.85 x 0.597 = 0.5%. Unlike the other uncertainty source, ε generates an almost negligible error.

4. Discussion

From the information summarized in Table 9, Figure 5 and the previous discussion, it can be generalized that, regardless of the case, the growing number of subscribers introduces a cost peak. This peak is noticed in scenario B, since scenarios A and C are the initial and ending points. Although subscribers grow for each year-scenario, its highest growth happens between scenarios A and B (13.461 billions) which is almost three times than the growth from scenario B to C (5.4 billions). This increases the total costs, which makes the slope steeper, as shown in Fig. 5.

Fig 5. Total aggregated costs (billion €) per scenario vs. TR for each case of use



For pessimistic scenarios (dashed lines), lines increased linearly through scenarios A, B and C. In this case, the TR increase is due to the RAN improvement. In this sense, lines become steeper for the first transition between scenarios A and B. So, all the TRs improve most in the transition from B to C, which makes deployment of the three cases of use as late in time as possible more desirable. Even so, eMBB is the most desirable one to be deployed in two stages. Furthermore, MCS behaves better than MIoT in the second transition, which would make MIoT the best option to deploy first.

For optimistic scenarios, in the eMBB use case the line becomes almost straight, what means that costs and TR grow accordingly. This perfectly corresponds to the vision of a wide range of applications for eMBB. An improvement in the technical KPIs would affect linearly the costs, which is the most consistent approximation. In the MCS and MIoT use cases, both lines follow a similar trend. The convex lines turn into concave ones, which suggests that the cost peak in the transition between 4G and 5G will be reduced significantly. Between these two cases of use, MCS is the one with a steeper slope in the second transition. So when the decision between these two is made, developing MIoT first would be recommendable, leaving MCS for a second development stage.

5. Conclusions

Although the development of 5G is still in early stages, and there is great technological, regulatory and economic uncertainty, it is necessary to begin to understand the implications that this new technology will have on the strategy, planning and budgeting of the actors involved, especially the operators. In this sense, this article throws light on the transition from 4G to 5G, with a techno-economic perspective. By analysis of different technically evolving scenarios, this study defines an annotated roadmap which could provide useful insights about the most suitable use cases for deployments. Moreover, we propose a basic mathematical model which reinforces the feasibility of these use cases by optimizing their deployment costs and perform a local method sensitivity analysis based on partial derivatives with respect to the main parameters.

This investigation provides operators with useful strategy insights on the opportuneness and affordability of the scenarios and their order for commercial success: As has been said, eMBB remains the most desirable scenario for deployment in two stages. Conversely, MCS behaves better in the second transition than MIoT, making MIoT the best option to deploy first. Sensitivity analysis of the intermediate scenario, the one with even greater uncertainty, shows the robustness of the analysis which gives a maximum deviation of about 10% for the most feasible scenario, in relation to the weight of the RAN considered, and an almost negligible error.
Additionally, pessimistic vs. optimistic forecasts are discussed, allowing different insights even if the timeframe deviates, with regard to how the TR increases, in comparison to cost increases. The optimistic assumption would mean that, since the RAN has more weight in the TR, investments would be adequately made when Scenario B were chosen as the transition. On the other hand, for the pessimistic assumption, the opposite would happen, as shown in the graph in Figure 5.
The results clarify the key topic under study: What is the best transition scenario between 4G and 5G? Scenario B was chosen according to source [3]; however, there could be other recommended scenarios [29], as long as technical performance of the network is more dependent on the RAN.
Finally, to round up the findings of this research definitively, its main results can be expressed in a Recommendation Score (RS) of use to operators, suppliers and practitioners. This RS ranges from 0 to 3, matching case of use and scenario (Table 10), where 0 means totally unrecommendable, and 3 totally recommendable. This RS completes the conclusions and reasoning given throughout the whole paper, providing useful insight for the different actors and investors involved in deployment of 5G networks, to support their strategic and investment decisions.

Table 10. Recommendation scores for every case of use-scenario situation

		Scenario A	Scenario B	Scenario C
Recommendation Score (RS)	EMBB	2	2	3
	MIoT	3	1	0
	MCS	0	1	3

In summary: 1) eMBB seems adequate for both transitions, reaching the best TR among all the cases of use. However, the most demanding applications should be developed in the last stage. 2) MIoT is a case of use which is already being covered to a satisfactory level with current LTE networks, due to the lack of demanding KPIs. Therefore, Scenario A represents the best result and so it has the highest RS. 3) MCS stringent requirements such as latency and mobility require the arrival of scenario C to implement these cases of use applications, being the first scenarios totally non-recommendable.
This paper has certain limitations, mainly because of the lack of 5G "ready system" standards and the scarcity of similar techno-economic experiences for comparison. The economic analysis has only analyzed the costs, and obviously cannot foresee the associated potential revenues. Fortunately, this will be improved as research in this field increases. In any event, our results are relevant because they might help improve the conceptualization, technical design and economic success of future 5G networks, and contribute to fill the techno-economic gap in the nascent 5G literature.

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