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# A Techno-Economic Framework for 5G Transport Networks

Forough Yaghoubi, Mozhgan Mahloo, Lena Wosinska, Paolo Monti, Fabricio de Souza Farias, João Crisstomo Weyl Albuquerque Costa, and Jiajia Chen

## Abstract

Wireless heterogeneous networks (HetNets) are a cost- and energy-efficient alternative to provide high capacity to end users in the future 5G communication systems. However, the transport segment of a RAN poses a big challenge in terms of cost and energy consumption. In fact, if not planned properly, its resulting high cost might limit the benefits of using small cells and impact the revenues of mobile network operators. Therefore, it is essential to be able to properly assess the economic viability of different transport technologies as well as their impact on the cost and profitability of a HetNet deployment (i.e., RAN plus transport). This article first presents a general and comprehensive techno-economic framework able to assess not only the TCO but also the business viability of a HetNet deployment. The framework is then applied to the specific case study of a backhaul-based transport segment. In the evaluation work two technology options for the transport network are considered (i.e., microwave and fiber) assuming both a homogeneous (i.e., macrocells only) and a HetNet deployment. Our results demonstrate the importance of selecting the right technology and deployment strategy in order not to impact the economic benefits of a HetNet deployment. Moreover, the results also reveal that a deployment solution with the lowest TCO does not always lead to the highest profit.

## Introduction

The exponential growth of data traffic, mainly driven by the increase in multimedia services and in the number of connected devices, forces mobile network operators (MNOs) to upgrade capacity of their radio access networks (RANs) [1]. Traditional solutions such as enhancing spectrum efficiency and/or adding macrocell sites are not very practical due to finite spectrum resources and high cost caused by deploying a large number of macrocells. Besides, macrocell sites are not efficient in serving indoor users, which are responsible for the major part of the total network traffic [2]. A promising solution for the capacity crunch envisioned in future fifth generation (5G) scenarios is to deploy wireless heterogeneous networks (HetNets), where high-power macro base stations ensure coverage, while less expensive outdoor/indoor small cells (placed close to the end users) provide capacity when and where needed [2].

Apart from quantifying the benefits of HetNet deployments in terms of spectrum and energy efficiency [3], an MNO also needs to analyze their cost and economic viability since the introduction of small cells in RANs significantly affects design of the transport segment [4]. Many existing studies (e.g., [5, 6]) assess the revenue of different HetNet deployment and management strategies. However, such works only focus on the RAN segment and do not yet take into account the transport network infrastructure, which aggregates the traffic from each cell to the evolved packet core (EPC). Therefore, a techno-economic analysis of the overall mobile network deployment (including both the transport and the RAN) is crucial in finding the most economically viable solution from the MNO's point of view. The work in [6] addresses this problem by considering both transport and RAN. However, this work takes into account total cost of ownership (TCO) only. On the other hand, calculating the TCO of a given mobile deployment solution is not sufficient to understand its profitability, which depends on many other factors, such as initial investment, user penetration, revenues during network operating phase, competitors, and regulations. Moreover, a dynamic analysis, which can take into account how these parameters vary in time, is vital for the economic viability assessment. This is because both the yearly cash flow and the net presented value (NPV) (i.e., two key parameters in assessing business viability) are time-dependent. Nevertheless, many existing studies that consider a dynamic analysis of cash flow and NPV either are focused only on the RAN segment and do not assess the overall mobile network (i.e., transport + RAN [7, 8]), or just investigate some specific scenarios (e.g., dedicated to sparsely populated areas [9]), lacking the necessary generality.

We propose a comprehensive techno-economic framework for a 5G transport segment, which complements the existing methodology for RAN, thus enabling an economic viability analysis of an overall 5G mobile network deployment. The proposed framework extends the TCO model presented in [10] by introducing a dynamic model that allows computing the value of the yearly TCO, cash flow, and NPV. This framework is general and can be applied to assess the economic feasibility of

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various 5G transport solutions (e.g., based on backhaul, fronthaul, and midhaul [1]). The use case analyzed in this article focuses on a mobile network with a backhaul-based transport segment only. Our results provide network operators with insight on:

- What type of transport technology (e.g., fiber or microwave) is the most cost-efficient for a specific RAN deployment (e.g., homogeneous or heterogeneous)
- How much money should be invested each year in order to provide sufficient capacity while maximizing the profit in the long run

Several case studies have been carried out using the proposed techno-economic framework.

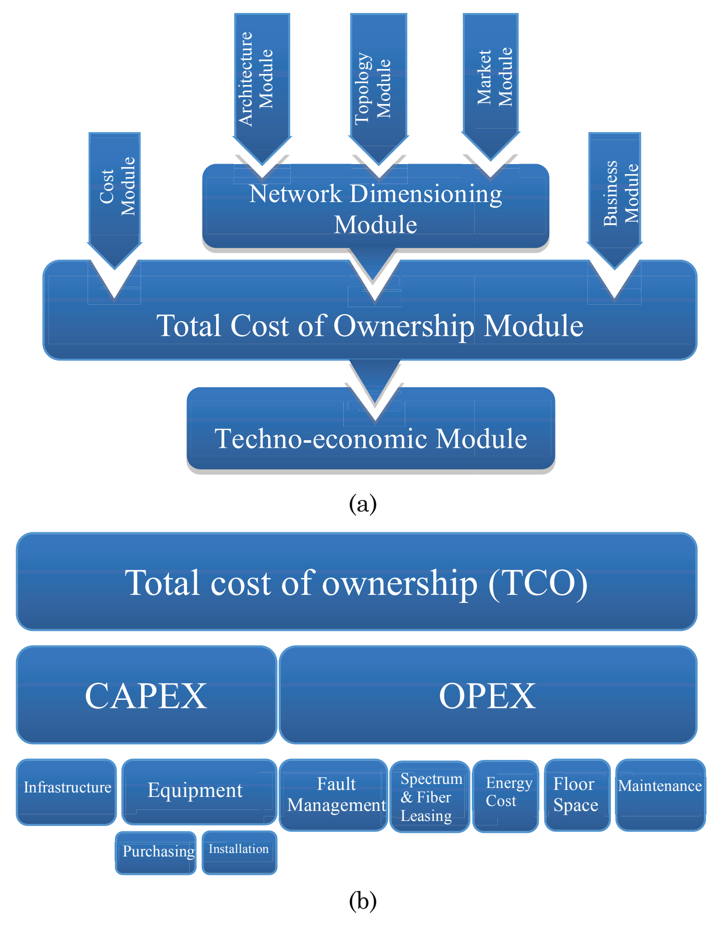

**FIGURE 1**. a) Techno-economic framework for the transport segment of a mobile network; b) cost classification of the TCO module.

## Business Feasibility Assessment of a Transport Segment

The life cycle of a communication network typically consists of four phases: planning, initial installation, operational phase, and migration. The *planning phase* takes place before any new deployment, and it is the most crucial step to understand if a deployment is profitable or not and to reduce the risk of investment. Even if a technology is already mature enough to be deployed, the market may not be ready; for example, the user penetration might be low. All these aspects need to be assessed via a comprehensive techno-economic study in order to validate the economic viability of a new deployment. In particular, it is crucial to quantify the total expenses required during the network operational time, as well as the estimated revenues and cash flows. This information should then be used to estimate the payback period, that is, the time required for the return of the investment. If the payback period is too long, or the total cash flow is negative, it is not advisable (from a pure economic point of view) to carry out the project. On the other hand, positive cash flow shows the business feasibility of the deployment. If the results from the planning phase show that a given deployment is profitable, the *initial installation* phase starts. Operators during this phase sustain a huge upfront investment that is typically considered as part of the capital expenditure (CAPEX). Once deployed, the network needs to be kept up and running (i.e., the *operational phase*), and the associated expenses are considered as part of the operational expenditure (OPEX). Finally, when the current network needs to be upgraded (e.g., a new technology is ready to be deployed), the customers' subscriptions will be gradually moved to the new/upgraded network (i.e., the *migration phase*). Some expenses related to this phase (e.g., the cost to set up, tear down, and change any running service) can be included in the OPEX, whereas the other migration related costs (e.g., purchasing new equipment) can be considered as the CAPEX.

Figure 1a presents an assessment methodology that can be used by mobile operators to analyze the business feasibility of a given transport deployment. This framework consists of several modules, described in the following sections.

### Architecture Module

The objective of this module is to define the technology used in the transport segment together with the type of components to be installed in each location. For example, in the case of a microwave-based transport, antennas are required on both sides of the microwave links, while in the case of a fiber-based transport optical line terminal (OLT), splitting devices and optical network units (ONUs) need to be installed at the central offices, remote nodes, and user premises, respectively.

### Topology Module

The network topology module defines the way in which the various components of a given architecture are interconnected, such as ring, star, tree, and mesh. Another important parameter included in the topology module is the demographical data of the region. The number of buildings, user density, size of the geographical region, and existing infrastructure (e.g., available ducts) are also input for the topology module, based on which the number of network nodes (e.g., central offices, remote nodes, cabinets), their locations, distances between different nodes, and equipment type that should be installed in each location can be determined. These parameters are then fed to the network dimensioning module.

### Market Module

When planning a network, it is crucial to consider market related data such as user penetration rate, operator's market share, user behavior, service prices, area throughput, quality of service (QoS), and connection availability. These parameters are fed to the market module, which in turn is able to estimate the possible revenues and the number of users that are expected to subscribe and unsubscribe to the service. The outputs of the market module are then inserted in the network dimensioning module.

### Network Dimensioning Module

By processing the inputs received from the architecture, topology, and market modules, this module calculates the amount of required new infrastructure (e.g., fibers, ducts, hubs) and the volume of components needed in the various network locations on a yearly basis. Moreover, the dimensioning module calculates the value of some operational parameters related to labor activities (e.g., traveling time to a certain network node for repair/maintenance).

By processing the inputs received from the architecture, topology, and market modules, this module calculates the amount of required new infrastructures and the volume of components needed in the various network locations on a yearly basis. Moreover, the dimensioning module calculates the value of some operational parameters related to the labor activities.

### Cost Module

A cost module is important for understanding how the various cost parameters in a TCO model vary with time. For example, the price of a specific component normally decreases due to technology maturation, whereas the expenses related to human resources (e.g., technician salaries) typically increase each year. Therefore, price variation should be considered while calculating the network expenses. Price erosion in time can be calculated via a learning curve that is used in the industry to predict the reduction of the cost of a product [11]. However, finding the right learning curve is not an easy task. The cost variation is often expressed by $P_j = P_0 + \alpha P_j - 1$, where $P_j$ denotes the price in year $j$ of the network operational time, $P_0$ is the initial price, and $\alpha$ denotes the cost change factor. Typically, $\alpha$ has a negative value for hardware components, while it has a positive value when salaries and energy cost are calculated. In general, $\alpha$ might also vary in time. However, for simplicity $\alpha$ is often assumed to be constant during the whole network operational time.

### Business Module and Scenarios

This module accounts for the business related parameters, and the cooperation models between actors and various governmental entities (e.g., municipalities). Business actors include physical infrastructure providers, network providers, service providers, and MNOs. Important business related parameters are the market share of each operator and regulations with respect to sharing the infrastructure. For example, if it is not possible to install separate network infrastructure for different MNOs inside a building, different MNOs may agree to share the common network infrastructure. Some possible business cases related to transport deployments are listed below, where we assume that an MNO is also a service provider.

**Case 1:** An MNO leases the transport network infrastructure.

**Case 2:** An MNO deploys its own transport network infrastructure.

There are two main business models for the access part when small cells are deployed: the closed subscriber group (CSG) and the open subscriber group (OSG) [6]. In the former case, only a closed group of users can access the indoor cells (i.e., it is considered as a private network for improving the service quality), and the MNO is not responsible for small cell deployment cost. In the latter case the small cells can be accessed by any users (i.e., regardless of their subscription), and the MNO is responsible for small cell deployment cost.

### Total Cost of Ownership Module

This section presents the total cost of ownership (TCO) module used in the proposed framework. The module covers both the CAPEX and OPEX aspects of the transport segment. Figure 1b shows the cost classification according to the proposed TCO module. Since in general a transport segment may use more than one technology (i.e., a hybrid architecture), the proposed module accounts for the presence of both fiber and microwave. Below, each component is briefly explained. For more details, we refer to [10] where the equations for calculating each cost factor are presented.

**Capital Expenditure:** CAPEX refers to all the expenses related to having the transport network in place. According to the proposed model (i.e., Fig. 1b), CAPEX can be divided into two main parts: equipment and infrastructure cost.

***Equipment Cost:*** Equipment cost is the sum of all expenses related to purchasing the transport network components according to the network dimensioning module and installing them in the assigned locations.

***Infrastructure Cost:*** Infrastructure cost corresponds to the investment that is needed to either deploy or lease the fiber infrastructure (including expenses of installing the microwave hubs, i.e., masts and antennas). In some cases, the infrastructure might already be deployed and owned by an MNO to accommodate other services (e.g., the fiber infrastructure is deployed for fixed broadband). This infrastructure can be reused by the MNO to provide backhaul connection at no cost.

**Operational Expenditure:** OPEX refers to the expenses during network operational time. The main OPEX components are indicated in Fig. 1b and defined below.

***Spectrum and Fiber Leasing:*** When leasing fibers, an MNO is charged a yearly fee for the maintenance and repair of the rented fibers in addition to the upfront expenses. In the case of a transport network based on microwave links, the operator needs to pay a fee for leasing the spectrum (usually defined on a per link basis) depending on the channel capacity and the frequency band.

***Energy Cost:*** The electricity bill is a part of the OPEX. This cost is obtained by summing up the energy cost of all the active equipment in the various locations of the transport network, including central offices, cabinets, microwave sites, and indoors.

***Maintenance Cost:*** The total maintenance cost is expressed as the sum of the maintenance cost of central offices, remote nodes, sites in the field (e.g., microwave sites), and yearly fee paid for the software licenses. To ensure that the network and all the services are running as expected, full-time monitoring is required. Therefore, the related expenses should be included in the maintenance cost. Monitoring expenses are not considered in [10], but can be simply calculated and added to the total maintenance cost as follows.

Assuming that one team of technicians can monitor up to $\beta$ nodes, dividing the total number of nodes ($N_j^{node}$) by $\beta$ gives the number of the required teams. $\text{Tech}_{te}$ and $\text{Tech}_j^{sal}$ denote the number of technicians per team and the hourly salary of each technician in year $j$, respectively. For a given network expected to operate for $L_n$ years, defined as operational time, the total monitoring cost (Mon) can be expressed as

$$\mathrm{Mon}=\sum_{j=1}^{L_n}(24\times 365)\mathrm{Tech}_{te}\left(\frac{N_j^{\mathrm{node}}}{\beta}\right)\mathrm{Tech}_j^{sal}. \qquad (1)$$

## FAULT MANAGEMENT

Fault management refers to the expenses related to the repair of the failures that might occur in the transport network. The total yearly repair cost is equal to the sum of the repair cost of each failure occurring during the year and the possible penalty paid to the users based on the service level agreement (SLA). The penalty cost is ignored in [10], but to get more accurate total cost, it should also be considered. Penalty is the fine that operators need to pay to customers when the service interruption is longer than the threshold defined in the SLA ($T_{tr}$). Let us define $t$ as a time period where $T_{tr}$ should be satisfied, which could be a year, a month, or a day depending on the SLA. If a failure happens in the transport segment in period $t$, one or more macrocells might be out of service, and a large number of customers can potentially be affected. Therefore, we consider the penalty that an MNO needs to pay when macrocell transport connectivity is lost, which can be calculated as

$$Penalty=\sum_{j=1}^{L_n}\sum_{i=1}^{N_j^{\mathrm{Mac}}}P_j^{co/h}(\mathrm{unAv}_{ij}\times t-T_{tr}), \qquad (2)$$

where $N_j^{\mathrm{Mac}}$ is the number of macrocells in the $j$th period of $t$, and $\mathrm{unAv}_{ij}$ represents the percentage of time when transport network connectivity to macrocell $i$ is not available during the $j$th period of $t$. $P_j^{co/h}$ shows the penalty fine rate that should be paid if the service interruption is longer than $T_{tr}$ defined as the penalty threshold in the SLA. $L_n$ represents the operational time of the network chosen according to time period $t$. For instance, when $t$ is equal to one year, $L_n$ corresponds to the total number of years that network is considered to operate. The transport segment provides the connectivity to the RAN. Therefore, if both access and transport segments are managed by the same MNO, the penalty caused by the problems occurring in the transport network will not be charged.

***Floor Space Cost:*** Floor space cost is a yearly rental fee paid by an operator for housing the equipment, that is, placing components in the racks with a standard size at various locations. In the case of a transport network, this cost includes the rental fee related to central offices, cabinets, and places for masts/hubs where the antennas are installed if, for example, microwave links are used to provide transport connectivity.

## TECHNO-ECONOMIC MODULE

The profitability of a network deployment project can only be calculated using a techno-economic analysis that includes cash flow and net present value (NPV) considerations. Let $CF_j$ denote the cash flow at the end of year $j$, which refers to the difference between the amount of money available at the beginning of year $j$ and the one 12 months afterward. In order to compute the value of $\mathrm{CF}_j$, we first calculate the yearly revenue by considering a constant subscription fee per month and per user (i.e., $\lambda$), and then derive the cost according to the TCO module $\mathrm{CF}_j = \lambda U_j - C_j$, where $U_j$ and $C_j$ represent the number of users and the TCO at year $j$, respectively. Knowing the cash flow for each year, the NPV that a project will bring with respect to the cash flow is computed as

$$NPV=\sum_{j=0}^{L_n}\frac{CF_j}{(1+r)^j}, \qquad (3)$$

where $L_n$ is the total operational years, and $r$ represents the discount rate for estimating the present value of the future cash flows by considering the time value of the money and the risk or uncertainties of the future incomes.

## CASE STUDY

This section presents a case study with a number of scenarios where the proposed business feasibility framework is applied. We calculate the overall cost to deploy and operate a mobile network including both the transport and RAN segments considering a network operational time of 10 years. In general, a backhaul network can be based on wired or wireless solutions. Currently, copper, fiber, and microwave are the dominating backhaul technologies.

By 2020, copper-based backhaul is expected to be replaced by the other technologies due to its limited ability to provide high capacity over long distances [2], which is obviously insufficient in the future 5G environment. Therefore, in this section, we focus on fiber and microwave-based backhaul solutions with sustainable data rates higher than 100 Mb/s per building or per cell [2].

### DESCRIPTION OF THE STUDIED SCENARIOS

The *topology module* considers a 5 km × 5 km dense urban area representing an average European city with a user population density of 3000 users/km$^2$. The area consists of 100 multistory buildings/km$^2$, with five floors per building and two apartments per floor. The buildings are placed according to the Manhattan street model [12], which is a widely considered geometric model in dense urban areas. We consider a tree topology for both the fiber- and microwave-based backhaul architectures.

The *architecture module* assumes two options for the wireless deployment, namely homogeneous (i.e., using macro base stations only) and heterogeneous (i.e., macro base stations serve outdoor users, while small cells are deployed inside the buildings to provide coverage for indoor users). The guaranteed data rate for backhaul links is assumed to be 300 Mb/s per building and 600 Mb/s per macrocell, respectively. Two backhaul technologies are considered in the case study: microwave and fiber. In the microwave backhaul, the traffic of the small cells inside a building is aggregated by an Ethernet switch with fast Ethernet connections, and then sent to a microwave antenna placed on the roof. The point-to-point microwave links are used to backhaul not only the data traffic aggregated from several small cells deployed in one building but also the traffic from the macrocells. The aggregated data from both macrocells and small cells is transmitted via point-to-point links between microwave antennas and an intermediate microwave hub, which is connected to the core

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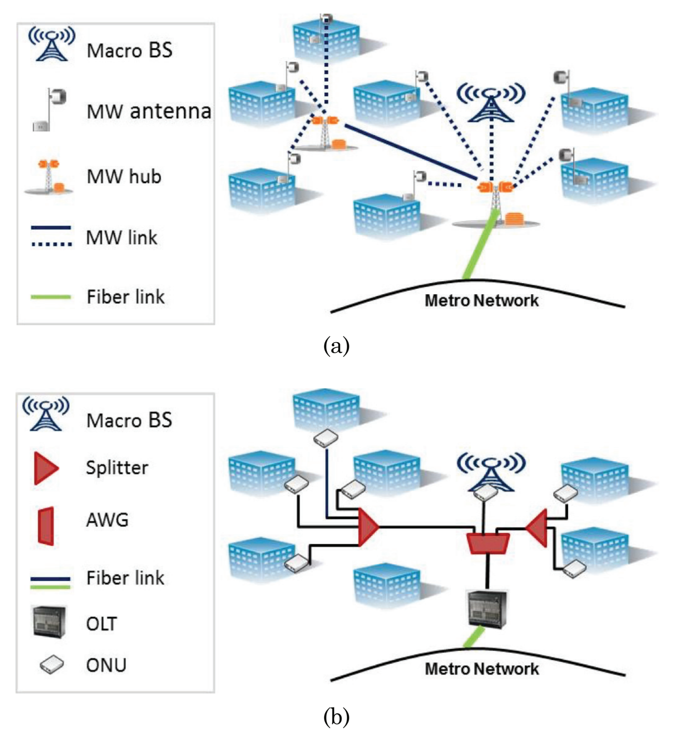

**FIGURE 2.** a) Microwave-based backhaul architecture; b) fiber-based backhaul architecture.

| | | | Heterogeneous | | Homogeneous |
|---|---|---|---|---|---|
| Year | Customer penetration | Capacity requirement (Mb/s/km$^2$) | Macrocell | Small cell | Macrocell |
| 0 | 5% | 15 | 4 | 2500 | 8 |
| 2 | 10% | 30 | 6 | 4000 | 15 |
| 4 | 15% | 60 | 9 | 5750 | 30 |
| 6 | 25% | 119 | 18 | 7500 | 60 |
| 8 | 50% | 235 | 36 | 10,000 | 119 |
| 10 | 70% | 470 | 72 | 12,500 | 237 |

**TABLE 1.** Input of market module and number of required cells [14].

network, forming a tree topology (Fig. 2a). In the scenario with fiber backhauling, the traffic from the indoor users is aggregated with a switch inside the building, which is co-located with an ONU in the basement connected to an OLT (Fig. 2b). The macrocells are also backhauled in the same way. The MNO can either deploy its own fiber infrastructure (i.e., trenching its own fiber cables) or lease fiber in the case when an existing fiber infrastructure is already available in the considered area. It is assumed that the fiber backhaul is based on a hybrid time- and wavelength-division multiplexing passive optical network (TWDM PON), whose architecture is explained in detail in [13].

The *market module* considers the capacity requirement per square kilometer each year (Table 1) as well as the coverage constraint as the main criteria for the dimensioning of a RAN, which is fulfilled using macrocell and small cell deployments. We calculate the required number of macrocells and small cells based on the model presented in [14]. We assume that in each year half of the users are covered by the macrocell, while the other half are served by the indoor cells. The results of the dimensioning work for the RAN based on the inputs from the market module are shown in Table 1.

*Cost values* used to calculate the TCO are summarized in Table 2. The fault management cost is calculated based on the values in [15].

The *business module and scenarios* consider the OSG model for small cells, where indoor cells are managed and owned by the MNO. We assume that the operator has 30 percent of the market share in the region; that is, only 30 percent of the total users are considered for the revenue calculations [6].

Based on the aforementioned assumption, the following six deployment scenarios are considered for the case study.

**Scenario 1:** Homogeneous RAN deployment is backhauled via microwave links (Ho_MW).

**Scenario 2:** Microwave backhaul is used to serve a heterogeneous RAN deployment (He_MW).

**Scenario 3:** The operator deploys its own fiber infrastructure (i.e., trenching is required) to backhaul its homogeneous RAN network (Ho_Tr).

**Scenario 4:** The operator leases fiber to backhaul a homogeneous RAN network (Ho_Le).

**Scenario 5:** The operator deploys its own fiber infrastructure (i.e., trenching is required) to backhaul its heterogeneous RAN (He_Tr).

**Scenario 6:** The operator leases fiber to backhaul its heterogeneous RAN (He_Le).

The considered deployment process is mainly determined by the customer penetration rate (Table 1) as well as the capacity demand over the considered area. Depending on the increasing capacity requirements originating from users that grow in number year after year, additional macrocells and/or small cells are gradually deployed (the number of required small cells and macrocells for each year is reported in Table 1). In the scenarios with fiber trenching (i.e., scenarios 3 and 5), during the first year the operator deploys its own fiber infrastructures to each macrocell and small cell planned for the whole network operational time. However, in the scenarios where fibers are leased (i.e., scenarios 4 and 6), the operator pays just for leasing the fibers that are required during each year. In the scenarios with microwave backhauling, we assume that the installation of the sites for the rooftop antennas as well as the intermediate hubs is done in the first year, while more antennas required for backhauling the macrocell and/or small cells are deployed when needed.

## Techno-Economic Evaluation Results

The results of the techno-economic evaluation of the six above-mentioned scenarios are presented in this section. Figure 3a shows the TCO for the mobile network considering both the backhaul and RAN expenses during the network operational time of 10 years. The backhaul expenses are calculated based on the model presented earlier. The RAN expenses are computed using the model proposed in [6]. The cost for the RAN segment accounts for both CAPEX and OPEX. The CAPEX includes the cost of purchasing and installing the required equipment (i.e., small cells and macrocells) as well as infrastructures including renting the space for installing the equipment, while the annual OPEX is assumed to be 10 percent of the CAPEX [6]. It is evident that the backhaul expenses are not a negligible part of the TCO of the mobile network. In the case of HetNet deployment, the RAN cost significantly decreases compared to the homogeneous one. However, the backhaul cost for HetNets is more than double that of the homogeneous case regardless of the type of backhaul technology. In particular, HetNet deployment with microwave backhauling represents the most expensive option among all the considered scenarios. This is due to high component cost and the power consumed by the microwave links in an ultra-dense area. However, in the case of fiber-based backhaul, the more cells in the area, the higher the possibility to share the infrastructure. Therefore, fiber-based backhauling is more cost-efficient in areas with a high density of small cells, even if an operator needs to deploy its own fiber infrastructure. It is important to carefully choose the proper backhaul technology in order to minimize the impact of the backhaul cost on the TCO of a mobile network in a HetNet deployment.

In order to have an NPV analysis, a yearly cost evaluation is required. Figures 3b–3g show the cost evolution for all the considered scenarios during the network operational time. It can be seen that the yearly TCO distribution varies with the different scenarios.

Another interesting aspect presented in Figs. 3a–3g is the distinction between CAPEX and OPEX for the backhaul segment, which gives an idea of the dominant cost elements. For instance, for homogeneous wireless deployment with microwave backhaul (Ho_MW), the OPEX of the backhaul segment (BH_OPEX) represents a significant part of the total cost, and it increases considerably with the capacity growth. However, it is a very small portion in the cases of fiber-based backhaul with trenching (i.e., Ho_Tr and He_Tr), which require a high cost for the fiber infrastructure deployment (CAPEX).

Figure 3i shows the results of the NPV analysis for all the scenarios based on a yearly cost evaluation considering an average monthly subscription fee of €30 per user (for voice and data), a discount rate of 10 percent, and revenue depending on user penetration as shown in Fig. 3h. Except for the HetNet deployment with microwave backhaul (He_MW), all the other scenarios have a positive NPV and can be considered economically viable. The HetNet deployment with the leased fiber infrastructure for backhauling (He_Le) has the lowest TCO value among all scenarios, while the NPV analysis indicates that the Ho_Le deployment has the highest profitability. It is because in the case of He_Le most of the investment for both backhaul and RAN needs to be done in the first years. Normally, the money spent later has a lower NPV due to the potential earning capacity, inflation, and so on. Therefore, without bringing in sufficient income, a big investment in HetNet deployment in earlier years is not profitable in the long run. It is clearly shown that the TCO and the NPV do not always have the same trend. For example, the technology with the lowest TCO might not be preferable for a long-term investment.

Without bringing in sufficient income, a big investment in HetNet deployment in earlier years is not profitable in the long run. It is clearly shown that the TCO and the NPV do not always have the same trend. For example, the technology with the lowest TCO might not be preferable for a long-term investment.

| Description | Value |
|---|---|
| Number of team ($\beta$) | 1 |
| Cost change factor (salary) ($\alpha$) | 7 % |
| Cost change factor (hardware) ($\alpha$) | –3 % |
| Discount rate ($r$) | 10 % |
| Subscription fee ($\lambda$) | €30 |
| Number of tech./team ($Tech_{te}$) | 2 |
| Technician salary/hour ($Tech_j^{sal}$) | €52 |
| Energy cost/kWh | €0.1 |
| Indoor yearly rental fee/m$^2$ | €220 |
| Outdoor yearly rental fee/m$^2$ | €180 |
| Small/Large microwave antenna | €500/2000 |
| G-Ethernet switch | €1800 |
| Microwave hub + installation | €20,000 |
| Ethernet switch | €150 |
| Yearly spectrum leasing/MHz | €5 |
| OLT (4x10G array transceiver) | €7000 |
| ONU | €150 |
| Power splitter (1:16/1:32) | €170/340 |
| Fiber/km | €80 |
| Trenching/km | €45,000 |
| Leasing upfront fee/km | €800 |
| Yearly fiber leasing fee/km | €200 |
| Macro base station and cell site | €48,000 |
| Small indoor base station | €250 |

**TABLE 2**. Input values used for TCO calculation [4, 6,10, 13, 15].

## SENSITIVITY ANALYSIS

The impact of the uncertainty about the values of some important input parameters on the NPV results is analyzed in this section. Figure 4 presents the results of the sensitivity analysis. The parameters that have the greatest impact on the value of the total cost are identified for each scenario based on the cost breakdown of the backhaul segment shown in [10]. In the case of the microwave-based backhaul, power consumption and equipment costs are the most expensive elements, while in fiber-based solutions, the infrastructure cost related to trenching or leasing has the highest share in the total cost of the backhaul. The green lines in Fig. 4 represent the baseline results (e.g., the one calculated above) for each scenario, and the blue bars demonstrate their variation when the selected input parameters are changed. It can be seen that microwave-based solutions are the least profitable options among all the scenarios even if the price of the energy

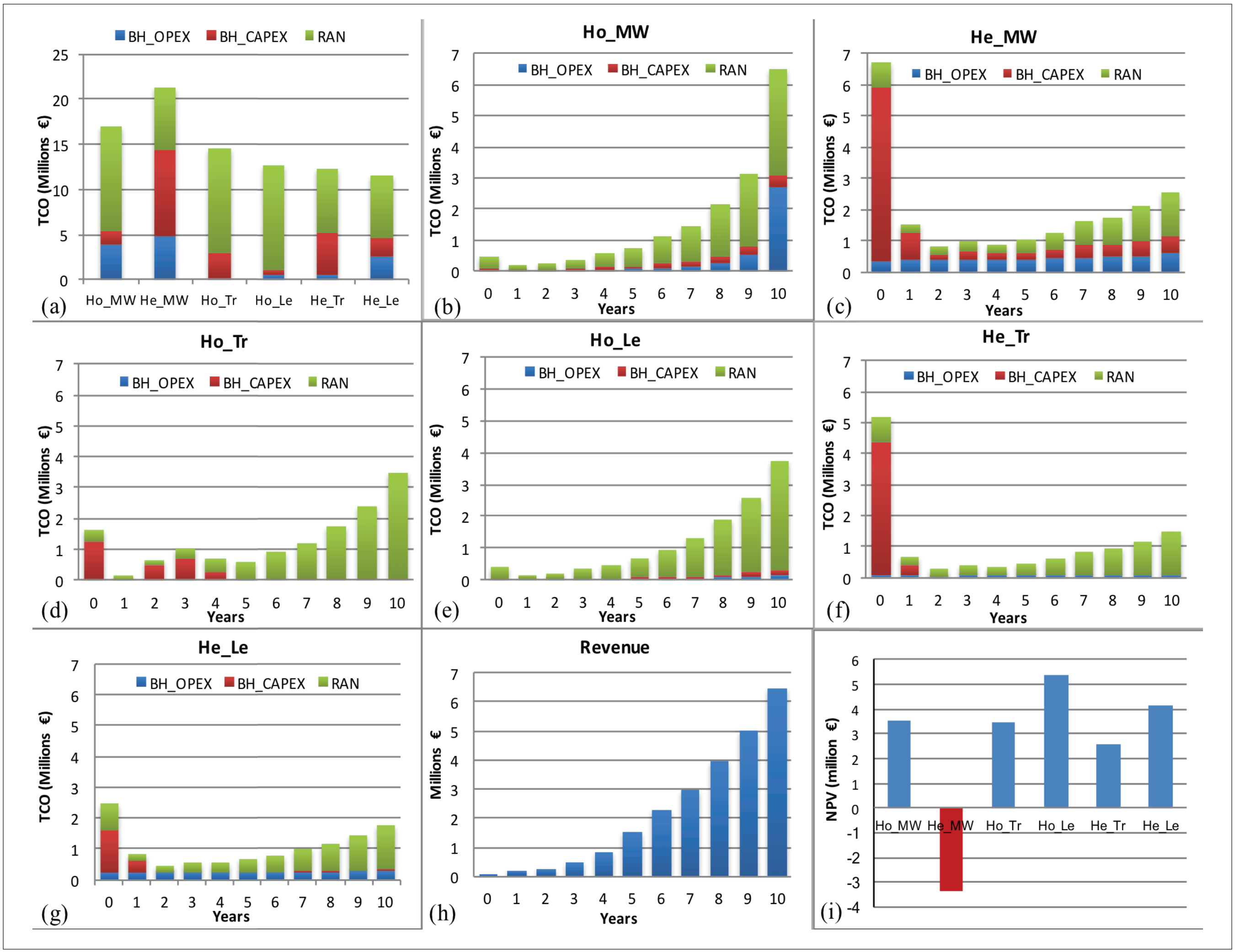

FIGURE 3. a) Total cost of ownership of a mobile network including both RAN and backhaul CAPEX (BH_CAPEX) and OPEX (BH_OPEX), TCO evolution per year for: b) scenario 1 (Ho_MW); c) scenario 2 (He_MW); d) scenario 3 (Ho_Tr); e) scenario 4 (Ho_Le); f) scenario 5 (He_Tr); g) scenario 6 (He_Le); h) yearly revenue; i) NPV at the end of the network operational time.

or the antennas changes within +/– 50 percent, which is in line with our previous observations. Another interesting conclusion from Fig. 4 is that if more than half of the required fiber infrastructure is already deployed, the He_Tr scenario offers the highest NPV for MNOs providing mobile services. Meanwhile, the price of leasing fibers, which varies a lot depending on the country and region, has great influence on NPV results. It can be seen that with a 50 percent increase in the leasing price, the fiber trenching and the fiber leasing solutions reach a similar level of NPV in HetNet deployment, while for homogenous deployment fiber leasing is always more attractive in terms of profitability. From Fig. 4, it can be inferred that in most cases the variation in the cost parameters are more critical in terms of NPV results in heterogeneous deployments than in homogeneous ones. Therefore, the cost parameters become crucial while estimating the profitability of a given HetNet scenario.

## CONCLUSIONS

This article presents a comprehensive techno-economic framework for analyzing the business viability of a given mobile network deployment (RAN plus transport) rather than purely estimating only its total cost of ownership. The case study carried out in this article focuses on a backhaul-based transport network using two technologies (i.e., microwave and fiber) and two types of wireless network deployments (i.e., heterogeneous and homogeneous). The results show a considerable increase of the backhaul TCO in the heterogeneous deployment compared to the homogeneous scenario. We highlight the importance of selecting the right backhaul technology in order to keep the cost savings and benefits brought by the heterogeneous deployments. This is particularly true in the case of future 5G mobile networks where high-capacity transport is required. We show that fiber is the most cost-efficient and profitable backhaul technology for heterogeneous wireless deployments in areas with high density of users. Moreover, the cheapest alternative is to lease fiber connectivity when possible and/or to maximize the possibility to reuse the available fiber infrastructure. Finally, regardless of the input parameters and considered scenarios that are applied for calculation, two general conclusions can be made based on the proposed framework for business viability assessment. First, a low TCO does not always lead to high profits. This is because in a long-term project, the point of time when an investment is made may significantly affect the total profit of the project. Second, in order to have a profitable solution, it is recommended to choose the technology or the deployment option that does not require a large upfront investment and that starts generating income as early as possible.

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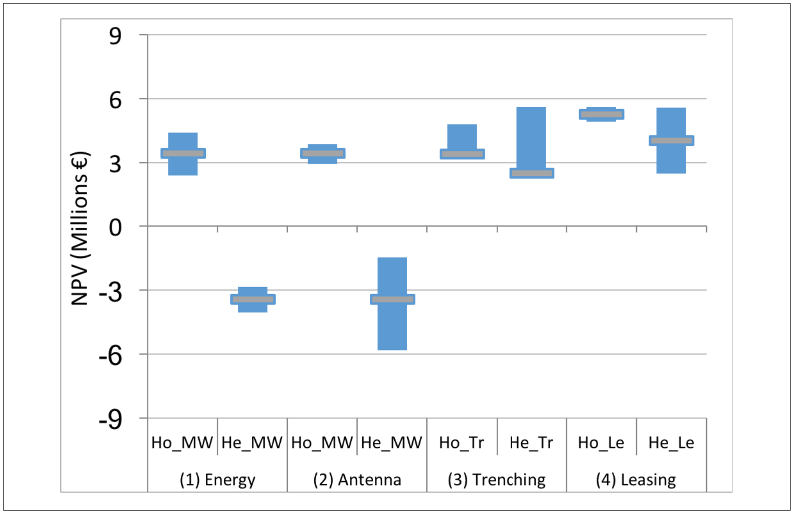

**FIGURE 4**. Sensitivity analysis of NPV varying: (1) energy price (± 50%), (2) MW antenna price (± 50%) (3) amount of re-usable trenching (from 0% to100%), (4) price of leasing (± 50%).

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