Game Theoretic Infrastructure Sharing in Multi-Operator Cellular Networks

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***Abstract*—The introduction of 4th Generation (4G) wireless technologies has fueled the rapid development of cellular networks, significantly increasing the energy consumption and the expenditures of the Mobile Network Operators (MNOs). In addition, the network underutilization during low traffic periods (e.g., night zone) has motivated a new business model, namely infrastructure sharing, that allows the MNOs to have their traffic served by other MNOs in the same geographic area, thus being able to switch off part of their network. In this paper, we propose a novel infrastructure sharing algorithm for multi-operator environments, which enables the deactivation of underutilized Base Stations (BSs) during low traffic periods. Motivated by the conflicting interests of the MNOs and the necessity for effective solutions, we introduce a game theoretic framework that enables the MNOs to individually estimate the switching off probabilities that reduce their expected financial cost. Our approach reaches a Dominant Strategy Equilibrium (DSE), which is the strategy that minimizes the cost of each player. Finally, we provide extensive analytical and experimental results to estimate the potential energy and cost savings that can be achieved in multi-operator environments, incentivizing the MNOs to apply the proposed scheme.**

***Index Terms*—Infrastructure sharing, Switching off, Base station sleep, Game theory, Energy efficiency**

I. Introduction

The rapid expansion of mobile services, along with the emerging demand for multimedia applications, driven by the widespread use of laptops, tablets and smart devices, has led to an impressive growth of the data traffic volume during the last few years. According to recent market predictions [1], global mobile data traffic is expected to increase nearly 11-fold in the next five years, reaching 15.9 exabytes per month by 2018. Hence, Mobile Network Operators (MNOs[1]) seek to extend their infrastructure by installing more Base Stations (BSs), in an effort to increase the capacity of their network and meet these pressing traffic demands.

The additional infrastructure not only implies a rise in the Capital Expenditures (CapEx), but also has a direct impact on the network energy consumption, thus resulting in higher Operational Expenditures (OpEx) [2]. In particular, the use of information and communication technology across a wide range of applications accounts for 5.7% of the world's electricity consumption and 1.8% of global carbon emissions [3], something that translates into electricity bills in the order of $\$10$ billion for the MNOs worldwide [4]. Hence, there is a strong motivation to investigate solutions to bring down the energy consumption and the cost of cellular networks, thus yielding both environmental and financial gains. Given that cellular networks are dimensioned according to peak-hour traffic demands, an effective approach towards this direction is to temporarily switch off part of the BS infrastructure that remains underutilized when the network traffic is low.

The coexistence of multiple MNOs in the same geographical area [5], due to legal regulations that obligate them to install their antennas on the same buildings, has motivated a new business model, known as infrastructure sharing [6], [7]. This new paradigm embraces a set of strategies that enable the MNOs to use their resources jointly to reach their common goal, which is to guarantee user service while achieving energy and cost reduction. Infrastructure sharing is classified into three categories [8]: *i*) passive sharing of sites, masts and building premises, *ii*) active sharing of the active network components such as antennas, switches and backhaul equipment, and *iii*) roaming-based sharing, where the MNOs share the cell coverage for a pre-negotiated time period.

In this paper, motivated by the aforementioned issues, we propose a roaming-based infrastructure sharing scheme, applicable in multi-operator environments during low traffic periods. Taking into account the rationality of the MNOs and their conflicting interests, we introduce a game theoretic framework that enables the MNOs to make individual switching off decisions for their own BSs, thus bypassing potential complicated service level agreements among them. Besides the expected energy efficiency benefits, the proposed scheme allows the MNOs to significantly reduce their financial costs independently of the strategies of the coexisting MNOs, providing them with the incentives to participate in the game. Our contribution is summarized as follows:

1) As a part of an integrated roaming-based infrastructure sharing scheme for multi-operator environments, we introduce a game theoretic switching off algorithm that aims at minimizing the individual MNO cost in a distributed manner. We define a realistic cost function that explicitly considers actual roaming and operational costs for the MNOs. We show that, in the proposed game, a

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[1]Hereafter, the terms "MNO" and "operator" will be used interchangeably.

Dominant Strategy Equilibrium (DSE) can be reached, defined as the strategy yielding the minimum cost for each MNO, regardless of the other MNOs' actions.
2) To address the heterogeneous nature of voice and data traffic in current and future cellular networks, we design an analytical model, based on a two-dimensional Markov chain, that theoretically estimates the throughput, the energy efficiency and the cost expenses both for the individual MNOs and the whole network.
3) We validate the theoretical analysis and assess the effectiveness of the proposed infrastructure sharing scheme with the aid of extensive simulation experiments. We introduce a new performance metric, namely cost efficiency, that connects the network performance with the financial benefits of the MNOs. The results indicate the potential total energy efficiency gains in the network and highlight the individual cost and energy gains for the MNOs.

The remainder of the paper is organized as follows. Section II briefly reviews the related work. The system model, the network configuration and the notation used throughout the paper are described in Section III. In Section IV, we introduce the infrastructure sharing scheme, along with the game formulation of the switching off decision. In Section V, we present the analytical models for the energy efficiency, the network throughput and the cost metrics. The validation of the model and an extensive performance assessment are provided in Section VI. Finally, Section VII concludes this paper.

II. Related Work

Since the BS is one of the most power hungry network components, several research works have focused on reducing the number of BSs through optimal [9], [10] or heterogeneous deployment strategies [11], [12]. Recently, in an effort to achieve more drastic energy saving gains, the research community has shifted towards the investigation of BS switching off schemes [13]-[17]. The core idea is to increase resource utilization during periods of low traffic (e.g., night) by switching off part of the BS infrastructure, while the remaining active BSs extend their coverage to serve the whole network area.

These traditional switching off schemes can be taken one step further by considering the emerging business model of infrastructure sharing among multiple MNOs offering service to the same geographical area. In particular, significant research attention has been placed on roaming-based infrastructure sharing solutions that consider joint BS switching off among multiple MNOs [18]-[22]. In [18], a non-cooperative game for switching off BSs in a two MNOs network is presented. In their pioneer work, Marsan and Meo [19] proposed four cooperative strategies to switch off BSs in networks with two MNOs, according to the following criteria: *i*) equal switching off time periods, *ii*) equal roaming costs, *iii*) equal energy gains, *iv*) maximum energy savings. In all cases, the traffic of the switched off BS is roamed to the collocated BS of the active MNO. In [20], the authors extend the algorithm that maximizes the energy savings (proposed in [19]) for multi-operator environments with various traffic types and Quality of Service (QoS) requirements (i.e., throughput, lost calls). In the same context, Oh et al. [21] studied the potential energy savings that can be achieved by opportunistically switching off part of the network during low traffic in real-world scenarios. In our former work [22], we introduced a game theoretic switching off strategy in networks with two MNOs, providing analytical expressions for the throughput and energy efficiency calculation, assuming only one type of traffic (i.e., voice).

Nonetheless, despite their novel insights in the infrastructure sharing concept, the aforementioned works study only particular aspects of the problem (e.g., switching off time, roaming cost, energy savings). However, to provide feasible and efficient solutions, it is necessary to take into consideration all the important parameters (i.e., roaming and operational cost, energy consumption, QoS in terms of lost calls). In addition, the consideration of only voice traffic in some works (e.g., [19], [20]) is not realistic, since data traffic forms a significant part of the total traffic load in current cellular networks. Last but not least, the assumption of only two MNOs in the network is a limiting factor for the contribution of the above works, as the most common scenarios in European countries involve three to four MNOs [5]. In the following sections, we propose a distributed BS switching off solution that enables the efficient infrastructure sharing in multi-operator networks, taking into account realistic cost and traffic patterns.

III. System Model

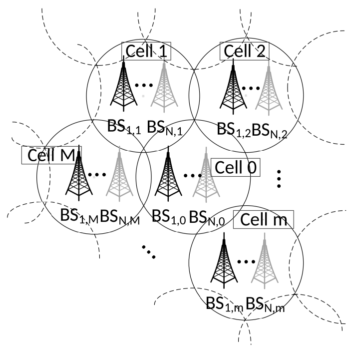
A. System Model and Operation

Our system model, depicted in Fig. 1(a), considers clusters of multi-operator cells. Each cluster is formed by one central cell surrounded by M peripheral cells, while each cell includes N BSs of different MNOs. Therefore, the term $BS_{n,m}$ is used to denote the BS of the nth operator in the mth macro cell, with $n \in [1, N]$ and $m \in [0, M]$. Part of the BS infrastructure in the M surrounding cells may be switched off during low traffic conditions, motivating the MNOs to share the resources of the remaining active BSs in the same cell. In contrast, the central cell BSs always remain active and increase their transmission power to form an umbrella cell, in the extreme case where all the BSs of a peripheral cell are switched off.

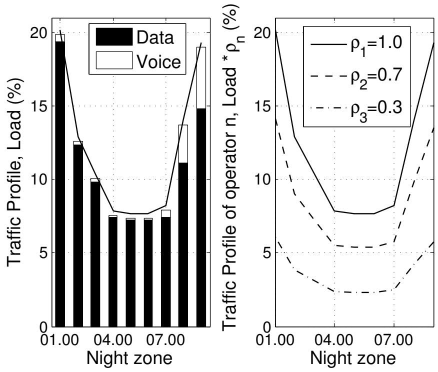
Regarding the traffic model, we adopt a realistic pattern [23]-[24] for the aggregate voice and data traffic per operator in a given cell during the night zone. As depicted in the leftmost part of Fig. 1(b), the maximum traffic per hour is expressed as a percentage of the total BS capacity BW that is considered same for all cells. We focus on the time zone between 01.00 and 09.00 am[2], when the total traffic per BS is relatively low (i.e., less than 20% of the cell's capacity).

For the sake of generality, we assume that the traffic of different operators follows the same pattern but may vary in volume. Hence, we define the percentage of each MNO's traffic load $\rho_n \in [0, 1]$ with respect to the maximum traffic for the respective hour. In the example depicted in the rightmost part of Fig. 1(b), the traffic of three MNOs is considered. The first MNO has the maximum traffic volume (i.e., $\rho_1 = 1$), whereas the second and the third MNO have 70% and 30% (i.e., $\rho_2 = 0.7$ and $\rho_3 = 0.3$) of the maximum traffic,

[2]Our algorithm can be adapted to different traffic conditions and the selection of the night zone may vary according to the actual traffic variations.



(a) Cluster of one central and M peripheral macro cells, covered by N operators



(b) Voice and data traffic during the night zone

Fig. 1. Scenario and traffic model

respectively. Finally, the voice and data connections are served at a Constant Bit Rate (CBR) of R_V and R_D, respectively[3].

B. Notation

Before proceeding to the algorithm description, let us define the next sets:

- $\mathcal{M} = \{1, \ldots, M\}$, with $|\mathcal{M}| = M$, is the set of peripheral cells forming a cluster around a central cell.
- $\mathcal{N} = \{1, \ldots, N\}$, with $|\mathcal{N}| = N$, is the set of N operators covering the cluster area.
- $\mathcal{M}_{ON} \subseteq \mathcal{M}$, with $|\mathcal{M}_{ON}| = M_{ON}$, is the subset of peripheral cells with at least one active BS.
- $\mathcal{M}_{OFF} \subseteq \mathcal{M}$, with $|\mathcal{M}_{OFF}| = M_{OFF}$, is the subset of peripheral cells with all BSs switched off.
- $\mathcal{N}_{ON}^{(m)} \subseteq \mathcal{N}$, with $\left|\mathcal{N}_{ON}^{(m)}\right| = N_{ON}^{(m)}$, is the subset of MNOs that maintain their BSs active in cell m.
- $\mathcal{N}_{OFF}^{(m)} \subseteq \mathcal{N}$, with $\left|\mathcal{N}_{OFF}^{(m)}\right| = N_{OFF}^{(m)}$, is the subset of MNOs that switch off their BSs in cell m.
- $\mathcal{N}_{roam}^{(n,m)} \subseteq \mathcal{N}_{OFF}^{(m)}$, with $\left|\mathcal{N}_{roam}^{(n,m)}\right| = N_{roam}^{(n,m)}$, is the subset of operators that select operator n in order to roam the traffic of their switched off BS in cell m.

IV. Infrastructure Sharing with Game Theoretic Switching Off Decision

In this section, we introduce the infrastructure sharing framework for multi-operator environments, consisting of two parts: *i*) an infrastructure sharing algorithm and *ii*) a game theoretic switching off decision strategy. The infrastructure sharing algorithm that defines the rules for the collaboration among the MNOs, given that part of the BS infrastructure is switched off during the night zone is presented in Section IV-A. Then, in Section IV-B, we formulate the BS switching off decision as a game theoretic strategy that enables each operator to determine the best course of action in each cell, in order to reduce its own cost and energy consumption.

A. Infrastructure Sharing Scheme

Let us recall that the considered system model (Section III-A) includes N MNOs that provide coverage to a cluster of one central and M peripheral cells. For the low-traffic night zone, a subset of each operator's BSs in the peripheral cells is switched off. Once this BS subset is determined (through the game theoretic algorithm described in the next section), the proposed infrastructure sharing scheme is applied to determine how the traffic will be served by the remaining active infrastructure, taking into account the corresponding operation and roaming costs.

The proposed infrastructure sharing scheme is applied in the network after the execution of the independent switching off decisions. According to the outcome of the decision process, there are three possible outcomes in a peripheral cell m:

1) If all the BSs remain active (i.e., $\mathcal{N}_{ON}^{(m)} = \mathcal{N}$), no infrastructure sharing takes place. Hence, each BS consumes energy for operation and service of its own traffic.
2) If a subset $\mathcal{N}_{ON}^{(m)} \subset \mathcal{N}$ of the BSs remains active, then they undertake the service of the traffic of the switched off BSs in the same cell (i.e., $\mathcal{N}_{OFF}^{(m)}$). In particular, the traffic of each switched off BS is roamed to an active BS of the same cell, selected randomly with equal probability p_s from the subset $\mathcal{N}_{ON}^{(m)}$. The MNOs of the deactivated BSs should pay the corresponding roaming cost to the active operators. However, the increased energy consumption (due to the higher traffic) of the active BSs implies a higher cost that should also be considered.
3) If no BSs remain active, (i.e., $\mathcal{N}_{ON}^{(m)} = \emptyset$), the BSs of the central cell ($BS_{n,0}$) increase their transmission power to cover the area of the peripheral cell. In this case, there is no collaboration between operators, since the traffic of each switched off BS is served by the central BS of the same operator. Hence, no roaming costs are involved, while the operators take into account the extra cost for the increased power consumption in the central cell.

Having defined the general network operation, each MNO is able to make an individual switching off decision without the need of exchanging information and, subsequently, to execute the infrastructure sharing algorithm (Algorithm 1), illustrated in Fig. 2. Given the aforementioned three possible outcomes for the peripheral cell m, four different cases can be observed from the point of view of the nth operator (i.e., MNO_n):

- *Case 1 - Operator n is ON and $N_{ON}^{(m)} = N - 1$ operators are ON*: The total cost for the MNO_n is $C_{n,m} = C_{const} + C_{tr}^{(n,m)}$, where C_{const} represents the fixed operational cost for the BS and $C_{tr}^{(n,m)}$ corresponds to the cost for serving the BS's traffic.

[3]We consider that no rate adaptation takes place within the cell and all users of a given service class are allocated the same amount of resources, calculated for cell edge users. Although this is the worst case scenario, our approach is suitable for our high-level study, while the optimized resource allocation (i.e., spectral efficiency) is not so critical during the night zone.

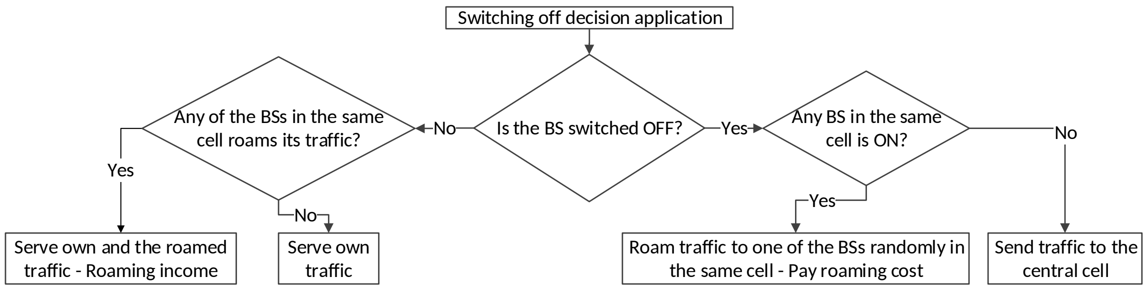


Fig. 2. Flowchart of the infrastructure sharing algorithm

- *Case 2 - Operator n is ON and $N_{OFF}^{(m)} > 0$ operators are OFF*: In this case, MNO_n may have to pay a higher cost due to the increased served traffic (i.e., its own traffic along with the roamed traffic of other BSs), while receiving the corresponding roaming income from each operator $MNO_i \in \mathcal{N}_{roam}^{(n,m)}$. More specifically:
  - The total operation cost can be expressed as $C'_{n,m} = C_{const} + C_{tr}^{(n,m)} + \sum_{i\in\mathcal{N}_{roam}^{(n,m)}} C_{tr}^{(i,m)}$
  - The received roaming income by MNO_n can be expressed as $C_{roam}^{'(n,m)} = \sum_{i\in\mathcal{N}_{roam}^{(n,m)}} C_{roam}^{(i,m)}$, where $C_{roam}^{(i,m)}$ is the roaming cost paid by MNO_i and can be considered as a portion of the total operational cost, i.e., $C_{roam}^{(n,m)} = \alpha \cdot \left(C_{const} + C_{tr}^{(n,m)}\right)$, with $\alpha \in [0, 1]$.

  Consequently, in this case, the total cost for operator MNO_n can be written as: $C_{n,m} = C_{const} + C_{tr}^{(n,m)} + \sum_{i\in\mathcal{N}_{roam}^{(n,m)}} C_{tr}^{(i,m)} - \alpha \cdot \left(C_{const} \cdot \sum_{i\in\mathcal{N}_{roam}^{(n,m)}} C_{tr}^{(i,m)}\right)$.
- *Case 3 - Operator n is OFF and $N_{ON}^{(m)} > 0$ operators are ON*: In this case, operator n should pay the roaming cost to one operator from the active set $\mathcal{N}_{ON}^{(m)}$ randomly selected with equal probability $p_s = 1/N_{ON}^{(m)}$. Hence, in this case, $C_{n,m} = C_{roam}^{(m,m)}$.
- *Case 4 - Operator n is OFF and $N_{OFF}^{(m)} = N - 1$ operators are OFF*: In this case, the cost paid by the MNO_n corresponds to the extra energy consumption for the power increase of the central BS ($BS_{n,0}$), in order to cover the area of a switched off BS in a peripheral cell. Hence, $C_{n,m} = C_{inc}^{(n,0)}$.

Algorithm 1 Infrastructure sharing algorithm of $BS_{n,m}$ in peripheral cell m

Require: Switching off decision of all MNOs in cell m
for each $m \in \mathcal{M}$ **do**
  for each $n \in \mathcal{N}$ **do**
    if $\left((n \in \mathcal{N}_{ON}^{(m)})\ \&\ (\mathcal{N}_{OFF}^{(m)} = \emptyset)\right)$ **then** ▷ Case 1
      $C_{n,m} = C_{const} + C_{tr}^{(n,m)}$
    else if $\left((n \in \mathcal{N}_{ON}^{(m)})\ \&\ (\mathcal{N}_{OFF}^{(m)} \neq \emptyset)\right)$ **then** ▷ Case 2
      $C_{n,m} = C_{const} + C_{tr}^{(n,m)}$
      for each $(r \in \mathcal{N}_{roam}^{(n,m)})$ **do**
        $BS_{n,m} \xleftarrow{roam} BS_{r,m}$
        $C_{n,m} = C_{n,m} + C_{tr}^{(n,m)} - C_{roam}^{(n,m)}$
      end for
    else if $\left((n \in \mathcal{N}_{OFF}^{(m)})\ \&\ (\mathcal{N}_{ON}^{(m)} \neq \emptyset)\right)$ **then** ▷ Case 3
      Select operator $r \in \mathcal{N}_{ON}^{(m)}$ with probability $p_s = 1/N_{ON}^{(m)}$
      $BS_{n,m} \xrightarrow{roam} BS_{r,m}$
      $C_{n,m} = C_{roam}^{(n,m)}$
    else if $\left((n \in \mathcal{N}_{OFF}^{(m)})\ \&\ (\mathcal{N}_{ON}^{(m)} = \emptyset)\right)$ **then** ▷ Case 4
      $BS_{n,m} \xrightarrow{roam} BS_{n,0}$
      $C_{n,m} = C_{inc}^{(n,0)}$
    end if
  end for
end for

B. Game Theoretic Switching Off Strategy

The proposed infrastructure sharing scheme defines the rules of agreement among the MNOs, taking as an input the subset of switched off BSs in the peripheral cells. Hence, the individual switching off decisions constitute the core of the proposed scheme and its main contribution. By considering the conflicting interests and the interaction among the MNOs, as well as the different available courses of action, we propose a game theoretic BS switching off strategy. We model the switching off decision process as a static non-cooperative game with complete information [25], played by the N MNOs in each of the M peripheral cells. Non-cooperative game theory provides multi-fold advantages, enabling us:

- to model the aforementioned conflicting situations between the MNOs with high accuracy;
- to minimize the exchange of information among the different MNOs. This is very important, since, in competitive environments, the MNOs may not be willing to disclose extensive network information to their competitors. Furthermore, minimizing interactions can reduce the risk of misbehavior, since selfish operators could choose to modify their statistics to increase their personal benefits;
- to reach distributed close-to-optimal solutions for realistic scenarios. In the proposed game, a DSE can be achieved, which can be easily calculated with limited required information. The DSE represents the solution where each player's assigned strategy minimizes its cost, regardless of the other players' strategy and, in our formulation, it is very close to the Pareto optimal solution.

The remaining of this section is divided into three parts. First, the game formulation and the cost matrix are given, followed by the individual cost minimization analysis in the second part. Finally, the DSE of the game is discussed, along with some numerical results on the switching off probabilities.

1) Game Formulation:

Definition 1. *The non-cooperative game Γ can be represented in strategic form by the triplet: $\Gamma = (\mathcal{N}, \mathcal{S}_{n,m}, C_{n,m})$, with $n \in \mathcal{N}, m \in \mathcal{M}$, where:*

- *$\mathcal{N} = \{1, \ldots, N\}$ is the finite set of players corresponding to the N operators.*
- *$\mathcal{S}_{n,m} = \{ON, OFF\}$ is the set of the two possible actions for each MNO_n with respect to the $BS_{n,m}$, i.e., $BS_{n,m}$ can be active (state ON) or switched off (state OFF).*
- *$C_{n,m} : \mathcal{S} \to \mathbb{R}^+$ is the cost function for player n in the peripheral cell m, where $\mathcal{S} = \mathcal{S}_{1,m} \times \cdots \times \mathcal{S}_{n,m} \times \cdots \times \mathcal{S}_{N,m}$ represents the Cartesian product.*

The cost function of the game $C_{n,m}$ has been selected to match the cost paid by each operator in every peripheral cell, as described in Section IV-A. However, exploiting the fact that the small traffic load variations during night have a negligible impact on the operational cost of the BS, it can be assumed that all operators have approximately the same cost for serving the traffic in a given cell m, i.e., $C_{tr}^{(n,m)} \approx C_{tr}^{(m)}$. Similarly, the roaming cost, which is expressed as a function of the operational cost, is also simplified to $C_{roam}^{(n,m)} \approx C_{roam}^{(m)}$.

This realistic simplification has two direct implications on the game formulation. First, the operators can accurately calculate their cost function by using average traffic statistics for a given cell. As a result, there is no need for information exchange among MNOs (to obtain the actual traffic values) prior to the application of the game, thus facilitating its implementation and eliminating any concerns about truthfulness. Second, by simplifying the cost functions, the MNOs obtain the same payoffs for a given action and, as a result, the outcome of the game is independent of the identity of the players. Hence, by definition, the proposed game is symmetric, allowing its formulation as an N-player game with 2 macro-players: *i*) player A is a given MNO_i, with $i \in \mathcal{N}$ *ii*) player B is the set $\mathcal{N} \setminus \{i\}$, formed by the remaining $N-1$ operators, excluding MNO_i. The matrix representation of the game is given in Table I, showing the costs of player A with respect to the different contingencies of player B.

The costs in Table I correspond to the different cases of the infrastructure sharing algorithm described in Section IV-A, after applying the simplification mentioned above. The formulation of our problem in a strategic form reveals one pure strategy, corresponding to the case where the MNOs switch off in all peripheral cells, thus minimizing the number of active BSs. However, this strategy would require major transmission power increase of the central BSs and could lead to lost sessions, since the central cells may not have sufficient capacity to support all the traffic of the cluster. This limitation of the pure strategy, along with the motivation of the MNOs to achieve energy efficiency without sacrificing ubiquitous service in the network, have motivated us to study the problem in the mixed strategies domain, in order to provide feasible and applicable solutions for distributed systems. Therefore, we proceed to a mixed strategy approach, where the MNOs randomize over the possible actions with a certain probability distribution. In the next section, we calculate the strategy that minimizes the cost of each player, and, then, by exploiting the symmetry of the game, we prove that a DSE is achieved.

2) Individual Cost Minimization Analysis:

The aim of the game is to calculate the set of the switching off probabilities that minimizes the expected cost of MNO_i, $\forall i \in N$, given by:

$$\begin{aligned}\mathbf{E}[C_{i,m}] = \mathbf{E}[C_{i,m}^{ON,ON}] + \mathbf{E}[C_{i,m}^{OFF,OFF}] \\ + \mathbf{E}[C_{i,m}^{OFF,ON}] + \mathbf{E}[C_{i,m}^{ON,OFF}].\end{aligned} \tag{1}$$

To that end, we define as $s_{i,m}$ the probability of player A (i.e., MNO_i) switching off the $BS_{i,m}$. Furthermore, due to the symmetry of the game, the remaining $N-1$ operators are grouped together into player B, having a common switching off probability $s_{j,m}$. Subsequently, the expected costs of player A in each state of the game are estimated as follows:

1) *Case 1 (ON,ON)*: The expected cost for MNO i is:

$$\mathbf{E}[C_{i,m}^{ON,ON}] = (1 - s_{i,m}) \cdot (1 - s_{j,m})^{N-1} \cdot \Big(C_{const} + C_{tr}^{(m)} \Big). \tag{2}$$

2) *Case 2 (ON,OFF)*: Each of the $N_{OFF}^{(m)}$ switched off BSs randomly selects one of the $N_{ON}^{(m)}$ active BSs of the same cell m with equal probability $p_s = 1/N_{ON}^{(m)}$. The random decision does not affect the outcome of our approach, since the roaming cost is indifferent to the BS selection. Hence, the number of switched off BSs that will select operator i to serve their traffic ($N_{roam}^{(i,m)}$) will determine its actual cost. To calculate the expected cost, all the possible roaming combinations that involve the ith operator must be considered, leading to Eq. (3) (top of the next page).
3) *Case 3 (OFF,ON)*: In this case, the traffic of the switched off $BS_{i,m}$ is roamed to one active BS, with a cost:

$$\mathbf{E}[C_{i,m}^{OFF,ON}] = s_{i,m} \cdot \Big(1 - (1 - s_{j,m})^{N-1} \Big) \cdot C_{roam}^{(m)}. \tag{4}$$

4) *Case 4 (OFF,OFF)*: The BSs of all operators are switched off and the traffic is served by the corresponding BSs of the central cell, which increase their transmission power to cover the peripheral cell, with an expected cost:

$$\mathbf{E}[C_{i,m}^{OFF,OFF}] = s_{i,m} \cdot s_{j,m}^{N-1} \cdot C_{inc}^{(i,0)}. \tag{5}$$

Substituting Eq. (2)-(5) to Eq. (1), we derive Eq. (6) at the top of the next page.

Let us recall that the goal of each MNO is to estimate its individual switching off probability that minimizes its cost. To that end, the strategy that minimizes the cost of the ith MNO, $s_{i,m}$, given the strategy $s_{j,m}$ is calculated by the roots of the partial derivative of the cost function with respect to $s_{i,m}$:

$$\begin{aligned}&\frac{\partial \mathbf{E}[C_{i,m}]}{\partial s_{i,m}} = 0 \Rightarrow s_{j,m}^{N-1} \cdot C_{inc}^{(i,0)} + \Big(1 - (1 - s_{j,m})^{N-1} \Big) \\ &\cdot C_{roam}^{(m)} - \sum_{N_{ON}^{(m)}=1}^{N} \binom{N-1}{N_{ON}^{(m)} - 1} \cdot (1 - s_{j,m})^{N_{ON}^{(m)} - 1} \cdot s_{j,m}^{N - N_{ON}^{(m)}} \\ &\cdot \left[C_{const} + C_{tr}^{(m)} + \Big(C_{tr}^{(m)} - C_{roam}^{(m)} \Big) \cdot \frac{N - N_{ON}^{(m)}}{N_{ON}^{(m)}} \right] = 0.\end{aligned} \tag{7}$$

TABLE I
COST MATRIX OF THE PROPOSED GAME

		Player B: $N-1$ operators in $\mathcal{N} \setminus \{i\}$	
		ON	**OFF**
Player A: Operator i	**ON**	$C_{const} + C_{tr}^{(m)}$	$C_{const} + C_{tr}^{(m)} + \left(C_{tr}^{(m)} - C_{roam}^{(m)}\right) \cdot N_{roam}^{(i,m)}$
	OFF	$C_{roam}^{(m)}$	$C_{inc}^{(i,0)}$

$$\begin{aligned}\mathbf{E}[C_{i,m}^{ON,OFF}] = &\sum_{N_{ON}^{(m)}=1}^{N-1} (1-s_{i,m}) \cdot \binom{N-1}{N_{ON}^{(m)}-1} \cdot (1-s_{j,m})^{N_{ON}^{(m)}-1} \cdot s_{j,m}^{N-N_{ON}^{(m)}} \cdot \Bigg[\sum_{N_{roam}^{(i,m)}=0}^{N-N_{ON}^{(m)}} \binom{N-N_{ON}^{(m)}}{N_{roam}^{(i,m)}} \cdot p_s^{N_{roam}^{(i,m)}} \\ &\cdot (1-p_s)^{(N-N_{ON}^{(m)}-N_{roam}^{(i,m)})} \cdot \left(C_{const} + C_{tr}^{(m)} + \left(C_{tr}^{(m)} - C_{roam}^{(m)}\right) \cdot N_{roam}^{(i,m)}\right) \Bigg] = \\ &\sum_{N_{ON}^{(m)}=1}^{N-1} (1-s_{i,m}) \cdot \binom{N-1}{N_{ON}^{(m)}-1} \cdot (1-s_{j,m})^{N_{ON}^{(m)}-1} \cdot s_{j,m}^{N-N_{ON}^{(m)}} \cdot \left[C_{const} + C_{tr}^{(m)} + \left(C_{tr}^{(m)} - C_{roam}^{(m)}\right) \cdot \frac{N-N_{ON}^{(m)}}{N_{ON}^{(m)}}\right].\end{aligned} \tag{3}$$

$$\begin{aligned}\mathbf{E}[C_{i,m}] = &\, s_{i,m} \cdot s_{j,m}^{N-1} \cdot C_{inc}^{(i,0)} + s_{i,m} \cdot \left(1-(1-s_{j,m})^{N-1}\right) \cdot C_{roam}^{(m)} + \sum_{N_{ON}^{(m)}=1}^{N} (1-s_{i,m}) \cdot \binom{N-1}{N_{ON}^{(m)}-1} \\ &\cdot (1-s_{j,m})^{N_{ON}^{(m)}-1} \cdot s_{j,m}^{N-N_{ON}^{(m)}} \cdot \left[C_{const} + C_{tr}^{(m)} + \left(C_{tr}^{(m)} - C_{roam}^{(m)}\right) \cdot \frac{N-N_{ON}^{(m)}}{N_{ON}^{(m)}}\right].\end{aligned} \tag{6}$$

Having provided the analysis for the individual cost minimization strategy, in the following section, we exploit the symmetry of the game to prove that the estimated value for the $s_{j,m}$ corresponds to the DSE.

3) DSE Characterization and Numerical Results: According to [26, Definition 3.4]:

Definition 2. *A strategy profile $\mathbf{s}^* = \{s_1^* \dots s_n^*\} \in \mathcal{S}$ is the DSE if each element s_i^* of $\mathbf{s}^*$ is dominant strategy of player i.*

Proposition 1. *The equilibrium of the game Γ is a DSE and is calculated by Eq.* (8) *at the top of the next page.*

The proof of the Proposition 1 is given in Appendix A.

Proposition 2. *The DSE of the game Γ is unique.*

The proof of Proposition 2 is given in Appendix B.

Unlike other widely-employed game theoretic concepts (e.g., Nash Equilibrium) that may require a number of iterations before converging to an acceptable solution [27]-[29], DSE can be always achieved in one shot. This is very important in our case where multiple iterations cannot be implemented, given that the continuous interchangeable switching on and off of the macro BSs is not considered as a viable option by the mobile operators [26], [30]. However, our practical and realistic game formulation enables the MNOs to reach the DSE by estimating one-shot switching off probabilities, which is particularly important in our problem. Hence, instead of applying an iterative algorithm that follows the best response dynamics to converge to an equilibrium, we show that one MNO can estimate the switching off strategies by knowing only the total number of operators (N) in the network.

Having derived the theoretical expression for the mixed strategies DSE, we study the impact of the number of MNOs and the roaming cost parameter α on the switching off probabilities through some numerical results, presented in Table II. The cost values are calculated based on the average traffic volume, given the Fig. 1(b). We consider values from $N=2$ up to $N=6$ operators, while we assume five different values for α ($\alpha=0.1$, $\alpha=0.3$, $\alpha=0.5$, $\alpha=0.7$ and $\alpha=0.9$) with respect to the definition of roaming cost in Section IV-A.

TABLE II
DSE SWITCHING OFF PROBABILITIES

N	$a=0.1$	$a=0.3$	$a=0.5$	$a=0.7$	$a=0.9$
2	0.459	0.377	0.296	0.215	0.133
3	0.679	0.629	0.568	0.486	0.357
4	0.799	0.749	0.675	0.584	0.466
5	0.854	0.826	0.795	0.758	0.713
6	0.880	0.861	0.843	0.819	0.798

Two main conclusions can be derived from Table II. First, the DSE switching off probabilities increase with the number of MNOs in each cell. In particular, the coexistence of many operators in one cell motivates a given MNO to switch off its BS, as it implies a higher probability of having its traffic roamed to a different MNO. Regarding the second basic observation, as expected, the switching off probability decreases for higher roaming cost, which is a prohibitive factor for the BS deactivation. However, it is worth noting that the DSE probability is severely reduced for higher roaming in networks with few MNOs, due to the risk of switching off all BSs in the cell. On the other hand, in a network with many MNOs, where the aforementioned risk is not so evident, the switching off probability for high a is still significant. Finally, in Appendix C, we compare the DSE to the global optimal solution to provide further insights for our game formulation.

V. ANALYTICAL MODEL

In this section, we provide analytical models for the calculation of the network throughput, energy efficiency and cost.

As mentioned in Section III-A, the network traffic consists of voice and data, with CBRs R_V and R_D, respectively. We assume that for each $BS_{n,m}$, voice calls and data sessions are Poisson generated processes with rates $\lambda_V^{(n,m)}$ and $\lambda_D^{(n,m)}$ and have exponential service times, denoted by $1/\mu_V^{(n,m)}$ and $1/\mu_D^{(n,m)}$, respectively. Hence, we model the operation of $BS_{n,m}$ as a multi-server $M_1, M_2/G_1, G_2/N/N_1, N_2$ queue,

$$s^{*N-1} \cdot C_{inc}^{(i,0)} + \left(1 - (1-s^*)^{N-1}\right) \cdot C_{roam}^{(m)} - \sum_{N_{ON}^{(m)}=1}^{N} \binom{N-1}{N_{ON}^{(m)}-1} \cdot (1-s^*)^{N_{ON}^{(m)}-1} \cdot s^{*N-N_{ON}^{(m)}} \cdot \left[C_{const} + C_{tr}^{(m)} + \left(C_{tr}^{(m)} - C_{roam}^{(m)}\right) \cdot \frac{N - N_{ON}^{(m)}}{N_{ON}^{(m)}}\right] = 0 \quad (8)$$

resulting in a two-dimensional Markov chain, illustrated in Fig. 3. Each state of the system (ν, d) is characterized by the number of active voice and data sessions, denoted by ν and d, respectively. The state space of this Markov model, along with the bandwidth restrictions, is:

$$\mathcal{A} = \{ (\nu, d) \,| 0 \leq \nu \leq N_V, \\ 0 \leq d \leq N_D, \nu \cdot R_V + d \cdot R_D \leq BW\}, \quad (9)$$

given that BW is the total bandwidth of the BS, $N_V = BW/R_V$ and $N_D = BW/R_D$ represent the maximum number of simultaneous voice calls and data sessions, respectively.

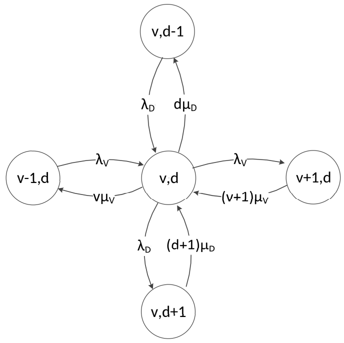


Fig. 3. Two-dimensional Markov state transition diagram for the voice and data traffic served in a BS (Note that for convenience, MNO and cell identification notations have been dropped.)

By analyzing the state transition diagram (Fig. 3), we obtain the system of linear equations for steady state probabilities, $p_{(\nu,d)}$. The balance equation that represents the valid transitions is given by Eq. (10) at the top of the next page.

The steady state probabilities are calculated given the condition that the sum of the state probabilities is equal to 1, i.e., $\sum_{\nu=0}^{N_V} \sum_{d=0}^{\lfloor \frac{BW-\nu \cdot R_V}{R_D} \rfloor} p_{(\nu,d)} = 1$. Employing the steady state probabilities, we calculate some key performance metrics for the individual BSs and the whole network.

A. Operator-wide performance metrics

In this section, we analyze the performance of a $BS_{n,m}$ with total bandwidth of BW, belonging to operator n in a given cell m. We focus on the night zone, with duration t_{night}, when voice and data sessions have an average generation rate of $\lambda_V^{(n,m)}$ and $\lambda_D^{(n,m)}$, respectively.

1) **Definition 3.** *Cell Throughput*: *The expected throughput $\boldsymbol{E}[T_{n,m}]$ for the $BS_{n,m}$ is defined as the average number (over all possible states) of served sessions in the system multiplied by the transmission rate of each session (i.e., R_V and R_D for voice and data, respectively) and calculated as:*

$$\boldsymbol{E}[T_{n,m}] = \sum_{\nu=0}^{N_V} \sum_{d=0}^{\lfloor \frac{BW-\nu \cdot R_V}{R_D} \rfloor} (\nu \cdot R_V + d \cdot R_D) \cdot p_{(\nu,d)}, \quad (13)$$

where $p_{(\nu,d)}$ are the steady state probabilities for the given traffic load rates $\lambda_V^{(n,m)}$ and $\lambda_D^{(n,m)}$.

A very important and relevant metric in our work is the normalized throughput, defined as the ratio of the served connections to the total existing connections in the network. This metric is often employed to represent the Grade of Service (GoS) in telecommunication systems, showing the level of user satisfaction in the system. Achieving a normalized throughput of 100% signifies that all users are served, which is a key requirement for MNOs.

2) **Definition 4.** *Cell Energy Efficiency*: *The expected energy efficiency $\boldsymbol{E}[\eta_\epsilon^{(n,m)}]$ for $BS_{n,m}$ is defined as the ratio of the average transmitted bits $\boldsymbol{E}[B_{n,m}]$ over the average energy consumption $\boldsymbol{E}[E_{n,m}]$:*

$$\boldsymbol{E}[\eta_\epsilon^{(n,m)}] = \frac{\boldsymbol{E}[B_{n,m}]}{\boldsymbol{E}[E_{n,m}]}, \quad (14)$$

where $\mathbf{E}[B_{n,m}]$ can be calculated by multiplying the average throughput (Eq. (13)) with the duration of the night zone (t_{night}), i.e., $\mathbf{E}[B_{n,m}] = \mathbf{E}[T_{n,m}] \cdot t_{night}$.

To calculate the average energy consumption, we consider the power consumed by the BS for operation and transmission, consisting of three components: *i*) the constant power P_{const}, consumed by an active BS for operations such as cooling, antenna feeding, etc, *ii*) the idle power P_{idle}, which is the power consumed when the BS remains idle, i.e., when it has no ongoing traffic sessions[4], and *iii*) the transmission power for serving the ongoing traffic sessions corresponding to each state $p_{(\nu,d)}$, considering that P_{tx} denotes the transmission power for serving a single voice or data session. Hence, the average energy consumption during the night zone t_{night} is given by:

$$\mathbf{E}[E_{n,m}] = \Bigg(P_{const} + P_{idle} \cdot p_{(0,0)} + \sum_{\nu=0}^{N_V} \sum_{d=0}^{\lfloor \frac{BW-\nu \cdot R_V}{R_D} \rfloor} (\nu + d) \cdot P_{tx} \cdot p_{(\nu,d)}\Bigg) \cdot t_{night}. \quad (15)$$

3) Cost: We provide analytical expressions for the different terms (i.e., C_{const}, $C_{tr}^{(n,m)}$, $C_{inc}^{(n,0)}$, $C_{roam}^{(n,m)}$) that compose Eq. (6), which provides the expected cost for an MNO.

First, C_{const}, $C_{tr}^{(n,m)}$ and $C_{inc}^{(n,0)}$ refer to the costs related to the operation of an active BS and the service of the existing traffic. These costs depend directly on the energy consumed for the different functions of the BSs. Therefore, provided that c_1 is the electricity charge per energy unit, in [€$/kWh$], the operational costs of a BS can be expressed as a function of the average energy consumption [31]. Thus, we have:

$$C_{const} = c_1 \cdot P_{const} \cdot t_{night}, \quad (16)$$

$$C_{tr}^{(n,m)} = c_1 \cdot \Bigg(P_{idle} \cdot p_{(0,0)} + \sum_{\nu=0}^{N_V} \sum_{d=0}^{\lfloor \frac{BW-\nu \cdot R_V}{R_D} \rfloor} (\nu + d) \cdot P_{tx} \cdot p_{(\nu,d)}\Bigg) \cdot t_{night}, \quad (17)$$

[4]The fraction of time that the BS remains idle is expressed by the probability $p_{(0,0)}$ in the Markov chain (Fig. 3).

$$p_{(\nu,d)} \cdot \left(\lambda_V^{(n,m)} \cdot \varphi_{\nu+1,d} + \lambda_D^{(n,m)} \cdot \varphi_{\nu,d+1} \cdot \vartheta_{\nu,d+1} + \nu \cdot \mu_V^{(n,m)} \cdot \varphi_{\nu-1,d} + d \cdot \mu_D^{(n,m)} \cdot \varphi_{\nu,d-1} \right) = \lambda_V^{(n,m)} \cdot p_{(\nu-1,d)} \cdot \varphi_{\nu-1,d}$$
$$+ \lambda_D^{(n,m)} \cdot p_{(\nu,d-1)} \cdot \varphi_{\nu,d-1} \cdot \vartheta_{\nu,d} + (\nu+1) \cdot \mu_V^{(n,m)} \cdot p_{(\nu+1,d)} \cdot \varphi_{\nu+1,d} + (d+1) \cdot \mu_D^{(n,m)} \cdot p_{(\nu,d+1)} \cdot \varphi_{\nu,d+1}, \quad (10)$$

where $\varphi_{\nu,d}$, $\vartheta_{\nu,d}$ denote the characteristic functions:

$$\varphi_{\nu,d} = \begin{cases} 1, & (\nu,d) \in \mathcal{A}, \\ 0, & \text{otherwise.} \end{cases} \quad (11) \qquad \vartheta_{\nu,d} = \begin{cases} 1, & \nu \cdot R_V + d \cdot R_D \le BW, \\ 0, & \text{otherwise.} \end{cases} \quad (12)$$

$$C_{inc}^{(n,0)} = c_1 \cdot \left(P'_{idle} \cdot p_{(0,0)} + \sum_{\nu=0}^{N_V} \sum_{d=0}^{\lfloor \frac{BW-\nu \cdot R_V}{R_D} \rfloor} (\nu+d) \cdot P'_{tx} \cdot p_{(\nu,d)} \right) \cdot t_{night}, \quad (18)$$

where P'_{idle} and P'_{tx} denote the power consumed when the BS remains idle and the transmission power for serving a single voice or data session, when the central BS increases its power.

With regard to the roaming cost, $C_{roam}^{(n,m)}$ corresponds to the amount paid when an operator roams its traffic to the BSs of another operator. In Section IV-A, the definition of the roaming cost with respect to C_{const} and $C_{tr}^{(n,m)}$ was given. Now, this definition is extended by considering the operational electricity charges. Based on the energy consumption of a BS, $\mathbf{E}\left[E_{n,m}\right]$, the roaming cost is given by:

$$C_{roam}^{(n,m)} = \alpha \cdot c_1 \cdot \mathbf{E}\left[E_{n,m}\right]. \quad (19)$$

4) Cost efficiency: Having defined theoretical expressions for the network performance and cost, we introduce a novel metric, named cost efficiency, that connects the performance with the total cost for each operator.

Definition 5. *Cell Cost Efficiency, measured in* $[Mbits/€]$, *is defined as the ratio of the average transmitted bits over the operator's total expenses. Accordingly, the cost efficiency of an operator* n *in a peripheral cell* m *is expresses as:*

$$\boldsymbol{E}\left[\eta_c^{n,m}\right] = \frac{\boldsymbol{E}\left[B_{n,m}\right]}{\boldsymbol{E}[C_{n,m}]}. \quad (20)$$

B. Network-wide performance metrics

In continuation, we calculate the respective metrics for the network of N operators in a cluster of one central and M peripheral cells. Based on the game theoretic analysis (Section IV-B), each operator n may choose to switch off the BS of a peripheral cell m with a switching off probability s^*. As explained before, depending on the case, the traffic of each switched off BS is served either by the central BS of the same operator, or by a different operator of the same cell.

To calculate the global performance metrics of the network, we calculate the average traffic load that is served by each BS after the application of the infrastructure sharing algorithm. We define as $\lambda_T^{'(n,m)}, T = \{V, D\}$ the new average traffic load of the $BS_{n,m}$ for voice and data traffic, which is equal to the traffic $\lambda_T^{(n,m)}$ of the nth MNO plus any additional roamed traffic. We distinguish the following two cases:

- For each $BS_{n,0}$ of the central cell:

$$\lambda_T^{'(n,0)} = \lambda_T^{(n,0)} + \sum_{i \in \mathcal{M}_{OFF}} \lambda_T^{(n,i)}. \quad (21)$$

- For each $BS_{n,m}$ of the peripheral cells ($m \in [1, M]$) that remains active and roams the traffic of $\mathcal{N}_{roam}^{(n,m)}$ MNOs:

$$\lambda_T^{'(n,m)} = \lambda_T^{(n,m)} + \sum_{i \in \mathcal{N}_{roam}^{(n,m)}} \lambda_T^{(i,m)}. \quad (22)$$

Using these values for the traffic load, the steady state probabilities $p'_{(\nu,d)}$ for each BS are recalculated and employed for the estimation of the key network metrics, explained below.

1) **Definition 6.** *Total Network Throughput: The total throughput of the cluster,* $\boldsymbol{E}\left[T\right]$, *is the sum of the average throughputs of the active BSs in the* M *peripheral cells and the central cell (which always remains active):*

$$\boldsymbol{E}\left[T\right] = \sum_{M_{OFF}=0}^{M} \binom{M}{M_{OFF}} \cdot {s^*}^{N \cdot M_{OFF}} \cdot \left(1 - {s^*}^N\right)^{(M-M_{OFF})}$$
$$\cdot \sum_{N_{OFF}^{(m)}=0}^{N-1} \binom{N}{N_{OFF}^{(m)}} \cdot {s^*}^{N_{OFF}^{(m)}} \cdot (1-s^*)^{N-N_{OFF}^{(m)}} \quad (23)$$
$$\cdot \left(\sum_{m \in \mathcal{M}_{ON}} \sum_{n \in \mathcal{N}_{ON}^{(m)}} \left(\boldsymbol{E}\left[T'_{n,m}\right]\right) + \sum_{n \in \mathcal{N}} \cdot \boldsymbol{E}\left[T'_{n,0}\right] \right),$$

where $\boldsymbol{E}[T'_{n,m}]$ *is the average throughput of an active* $BS_{n,m}$ *in cell* m*, calculated by Eq.* (13) *using the corresponding traffic load (Eq.* (22)*). Similarly,* $\boldsymbol{E}[T'_{n,0}]$ *is the average throughput of the central BSs, with average traffic load given by Eq.* (21)*.*

2) **Definition 7.** *Total Network Energy Efficiency: The total energy efficiency* $\boldsymbol{E}\left[\eta_\epsilon\right]$ *in the cell cluster is calculated as the total number of transmitted bits* $\boldsymbol{E}[B]$ *divided by the total energy consumption* $\boldsymbol{E}[E]$*:*

$$\boldsymbol{E}\left[\eta_\epsilon\right] = \sum_{M_{OFF}=0}^{M} \binom{M}{M_{OFF}} \cdot {s^*}^{N \cdot M_{OFF}} \cdot \left(1 - {s^*}^N\right)^{(M-M_{OFF})} \cdot \frac{\boldsymbol{E}[B]}{\boldsymbol{E}[E]}. \quad (24)$$

Similarly to Eq. (23), $\mathbf{E}[B]$ is calculated as:

$$\mathbf{E}\left[B\right] = \sum_{N_{OFF}^{(m)}=0}^{N-1} \binom{N}{N_{OFF}^{(m)}} \cdot {s^*}^{N_{OFF}^{(m)}} \cdot (1-s^*)^{N-N_{OFF}^{(m)}} \cdot$$
$$\left(\sum_{m \in \mathcal{M}_{ON}} \sum_{n \in \mathcal{N}_{ON}^{(m)}} \left(\mathbf{E}\left[B'_{n,m}\right]\right) + \sum_{n \in \mathcal{N}} \cdot \mathbf{E}\left[B'_{n,0}\right] \right), \quad (25)$$

where $\mathbf{E}[B'_{n,m}]$ and $\mathbf{E}[B'_{n,0}]$ the average transmitted bits for the BSs of the peripheral and the central cells, respectively, calculated for the corresponding traffic (Eq. (22) and (21)).

Accordingly, the total energy consumption is derived as:

$$\mathbf{E}\left[E\right] = \sum_{N_{OFF}^{(m)}=0}^{N-1} \binom{N}{N_{OFF}^{(m)}} \cdot {s^*}^{N_{OFF}^{(m)}} \cdot (1-s^*)^{N-N_{OFF}^{(m)}} \cdot \left(\sum_{m\in\mathcal{M}_{ON}} \sum_{n\in\mathcal{N}_{ON}^{(m)}} \left(\mathbf{E}\left[E'_{n,m}\right]\right) + \sum_{n\in\mathcal{N}} \cdot \mathbf{E}\left[E'_{n,0}\right] \right). \quad (26)$$

3) **Definition 8.** *Total Network Cost: The total cost of the network, $\boldsymbol{E}[C]$, is the sum of the average cost of all operators for the operation of their active BSs and for the service of the existing traffic load, estimated as:*

$$\boldsymbol{E}[C] = \boldsymbol{E}[E] \cdot c_1, \quad (27)$$

where $\boldsymbol{E}[E]$ is calculated by Eq. (26) for the average traffic served over a year. Apparently, the total network cost is not affected by the roaming cost, which only specifies the amount of money that is going to be exchanged among the operators.

VI. Performance Analysis

We have developed a custom-made C++ simulator for the network operation to validate the analytical expressions and assess the performance of the proposed infrastructure sharing scheme. In this section, we present the simulation setup along with the analytical and experimental results.

A. Simulation scenario

The simulation scenario considers a 7-cell cluster with one central and $M = 6$ peripheral cells. Each cell is served by N BSs of different MNOs, as described in Section III-A and up to $N = 6$ MNOs are considered in our experiments.

To assess the performance of our scheme, we compare the proposed Game Theoretic Infrastructure Sharing strategy (referred as GTIS hereafter) with three state-of-the-art approaches [19], [20]: *i*) aRoaming-to-One scheme (R-to-1), where the MNO with the highest traffic serves the total traffic in the network, while the rest MNOs switch off their BSs during the entire night zone, *ii*) a Roaming-to-All approach, namely Energy-balanced (E-bal), where the MNOs switch off their BSs for different portions of time to balance their energy saving, and *iii*) a Roaming-to-All approach, namely Roaming-balanced (R-bal), where the MNOs switch off their BSs for different portions of time to balance their roaming costs. In the Roaming-to-All strategies, the MNOs roam their traffic to all the active networks with a probability proportional to their network size. Moreover, we consider a baseline approach (No Switch Off), where all BSs are active. The simulation parameters are summarized in Table III.

B. Model Validation

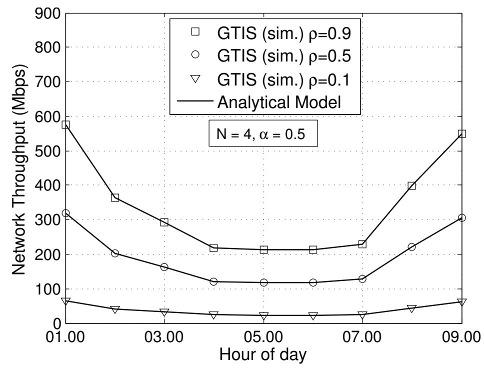
In this section, we validate via extensive simulations the analytical models for the network throughput, energy efficiency and network cost for different traffic profiles, roaming cost values and number of MNOs in each cell. In this set of experiments, we assume that all operators have the same traffic volume, i.e., $\rho_n = \rho$.

Figs. 4(a) and 4(b) present the total network throughput performance for different traffic profiles and number of MNOs, respectively. As we can see, the experimental results perfectly match the analysis, thus validating the proposed theoretical expressions. In both figures, we observe that the throughput presents similar behavior with the traffic load model (Section III-A). As expected, the network throughput also increases with the traffic load of each operator (ρ), as well as with the number of MNOs in each cell (N). It is worth mentioning that the roaming cost does not affect the throughput performance in the case of $N = 4$ MNOs, since there are no lost calls in the network. For higher number of operators, there are missed calls and this impact will be also studied in Section VI-D.

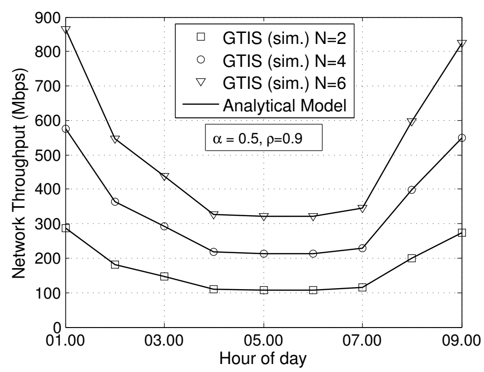
Figure 5 illustrates the total network energy efficiency achieved by the proposed infrastructure sharing policy for different traffic profiles (Fig. 5(a)), number of operators (Fig. 5(b)) and roaming cost values (Fig. 5(c)), which affect the switching off probabilities and, consequently, the total energy

TABLE III
SIMULATION PARAMETERS

Parameter	Value
Bandwidth, BW	115 Mbps
# of peripheral cells, M	6
# of operators, N	{2,4,5,6}
Traffic load, $Load$	Fig.1(b)
Traffic load ratio, ρ_n	[0.1, 1.0]
Service rates, μ_V, μ_D	Mean: 1/50 calls/s
Transmission rates, R_V, R_D	64, 256 kbps
Idle power, P_{idle}	[0.34, 1.39] W
Transmission power, P_{tx}, P'_{tx}	[1.29, 1.5] W
Constant power, P_{const}	[591, 675] W
Cell radius	[500, 1500] m
Night zone duration, t_{night}	$9 \cdot 3600$ s
Roaming cost variable, α	[0.1, 1.0]
Electricity charge, c_1	0.1 €/kWh

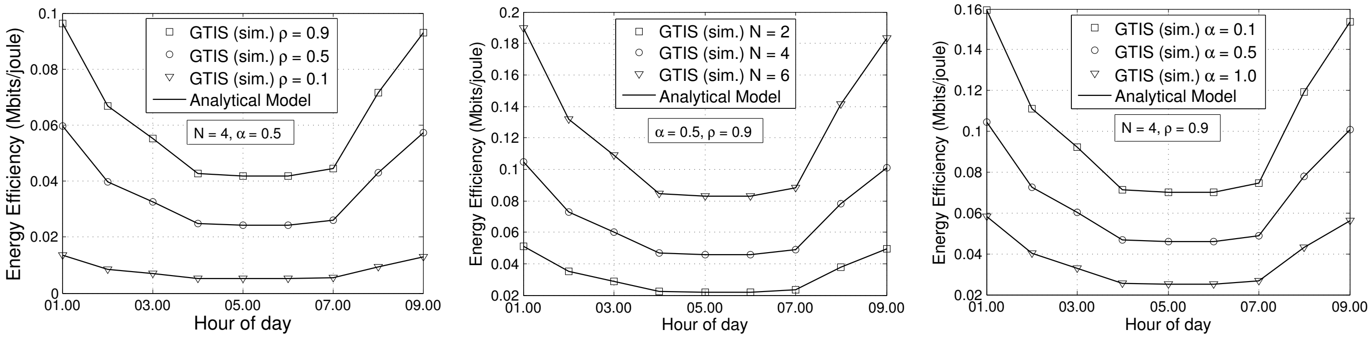


(a)



(b)

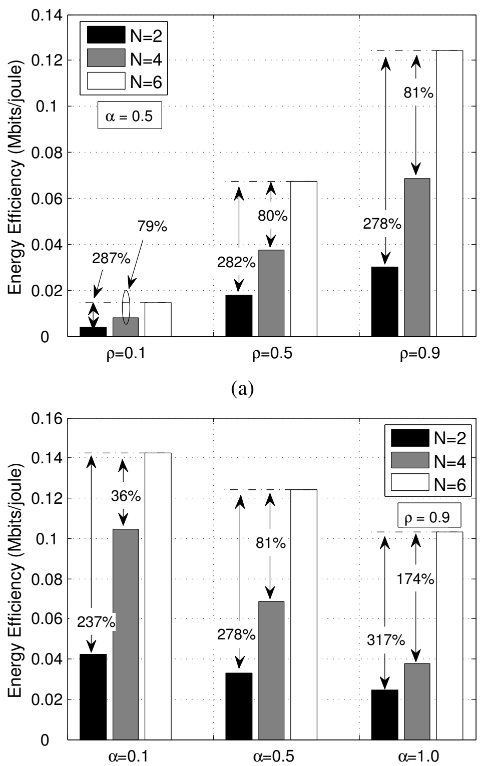
Fig. 4. Total network throughput validation for different (a) traffic profiles, (b) number of MNOs



(a) (b) (c)

Fig. 5. Total network energy efficiency validation for different (a) traffic profiles, (b) number of MNOs, and (c) roaming cost

efficiency. First, the analytical expressions given in Section V are again validated, while we observe a very similar behavior with the throughput case. More specifically, we observe that the network energy efficiency increases as the network becomes more loaded (i.e., for heavier traffic loads or higher number of operators). Hence, the proposed algorithm provides an effective energy efficient solution that encourages the operators to share their infrastructure in order to reduce the energy consumption. Furthermore, energy efficiency increases as the roaming cost drops, since lower roaming costs lead to increased switching off probabilities, as seen in Table II, thus reducing the energy consumption of the network.



(b)

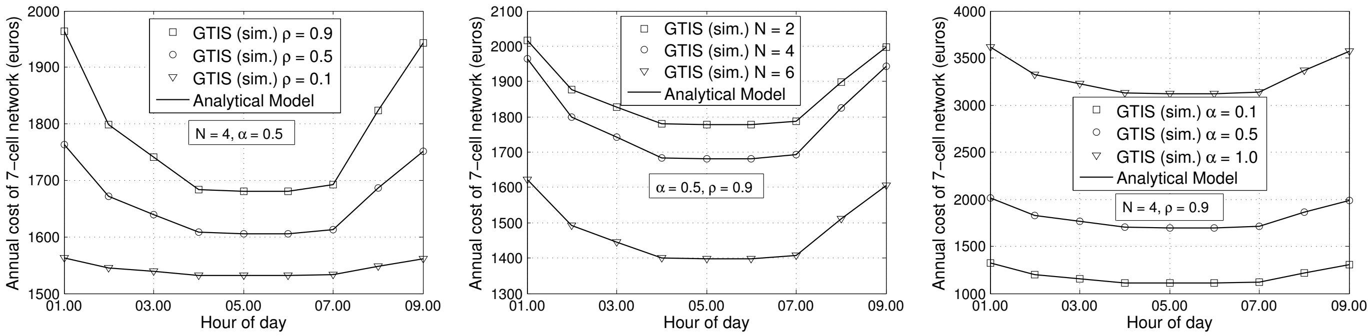
Fig. 6. Average network energy efficiency validation for different number of operators and different (a) traffic profiles, (b) roaming costs

In order to gain more insight on the network performance, we have plotted the average network energy efficiency during the night zone versus different traffic volumes (Fig. 6(a)) and roaming cost values (Fig. 6(b)). In Fig. 6(a), we observe that although the absolute value of the network energy efficiency increases with the number of operators, the relative difference ratio is independent of the traffic load. More specifically, in all cases, a network of $N = 6$ operators is approximately 80% and 280% more energy efficient compared to networks of $N = 4$ and $N = 2$ operators, respectively. This interesting fact can be explained by taking into account that the outcome of the game theoretic algorithm (i.e., switching off probabilities) is not affected by the traffic load variations. Referring to Table III, we observe that the difference between the constant power and the transmission power is significant. Thus, small variations on the traffic do not affect the probabilities calculation. On the other hand, as shown in Section IV-B3, the switching off probabilities strongly depend on the roaming cost, thus affecting the network energy efficiency (Fig. 6(b)). As also shown in Fig. 5(c), the energy efficiency is reduced as the roaming cost increases, while this impact is stronger for smaller number (N) of operators. However, the relative difference of the energy efficiency gain with respect to N increases for higher roaming costs. For instance, for low traffic loads ($\alpha = 0.1$), a network of $N = 6$ operators achieves 36% higher energy efficiency than a network of $N = 4$ operators, while this difference is considerably increased to 174% in case of $\alpha = 1.0$. This occurs because, even though the switching off probabilities are low for high roaming costs, the presence of more operators leads to a higher probability of sharing the infrastructure.

Figure 7 illustrates the total network annual cost for different traffic profiles (Fig. 7(a)), number of operators (Fig. 7(b)) and roaming cost (Fig. 7(c)). The analytical expressions given in Section V are again validated, while the results follow a very similar behavior with the throughput and energy efficiency only in the case of varying traffic profiles. On the other hand, the annual cost decreases with higher number of MNOs and decreasing roaming cost values. Given the switching off probabilities, depicted in Table II, in networks with high number of MNOs, the switching off probability increases, leading to smaller number of active BSs, which contribute to the total network cost according to Eq. (27). On the other hand, with increasing roaming cost, the MNOs are unwilling to switch off their BSs, resulting in higher aggregate cost.

C. Roaming Cost Analysis

The analysis and the experiments have revealed the criticality of the roaming cost parameter in roaming-based infrastructure sharing schemes. Therefore, the selection of an appropriate range of α for the performance evaluation of our proposal becomes of paramount importance. To that end, Fig. 8 presents the total network energy efficiency achieved



(a) (b) (c)

Fig. 7. Total network annual cost validation for different (a) traffic profiles, (b) number of operators, and (c) roaming cost

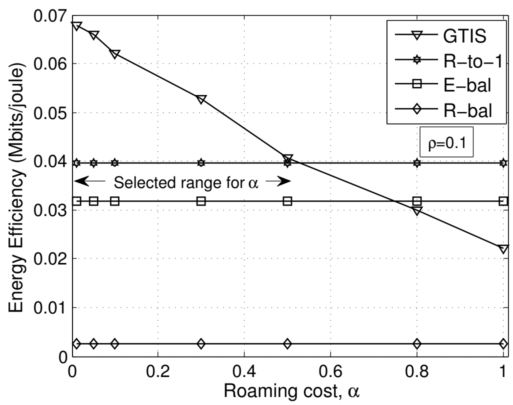


Fig. 8. Total network energy efficiency versus roaming cost to select the appropriate α

by the proposal compared to four schemes for the whole range of roaming cost values. We compare GTIS with the baseline scenario (i.e., No Switch Off) and three state-of-the-art approaches (i.e., R-to-1, E-bal and R-bal), which do not depend on the roaming cost. As we already mentioned, by employing the R-to-1, the MNO with heavier traffic load concentrates the traffic of the whole network, giving the opportunity to the rest of the MNOs to switch off their BSs. In E-bal and R-bal, the MNOs switch off their BSs for different portions of time in order to achieve equal energy gains and roaming costs, respectively. As a result, the switching off time of each MNO depends on their traffic load but is independent of the specific value of the roaming cost. In Fig. 8, we observe that GTIS outperforms R-bal independently of α, while there is an interesting trade off with regard to the R-to-1 and E-bal schemes. Our proposed solution achieves higher energy efficiency for low values of α (i.e., $\alpha < 0.5$ comparing to R-to-1 and $\alpha < 0.78$ comparing to E-bal). However, performance drops as the roaming cost increases and, for high α, R-to-1 and E-bal achieve higher energy efficiency compared to GTIS (i.e., $\alpha > 0.5$, $\alpha > 0.78$, respectively). When employing GTIS, the MNOs do not have a strong incentive to switch off their BSs for high roaming values. Since energy efficiency is one of the key goals of the proposed scheme, we focus on the values of α that ensure enhanced energy efficiency performance with respect to the state-of-the-art schemes (i.e., $\alpha \in [0, 0.5]$). Consequently, we have selected two indicative values of α within this range (i.e., $\alpha = 0.1$ and $\alpha = 0.5$) for the performance assessment of our proposed solution.

D. Performance evaluation

This section includes the performance results with regard to various metrics, either telecommunication - oriented (network throughput and energy efficiency) or cost - oriented (annual cost and cost efficiency). In order to generalize the assessment of our proposal, we consider different traffic volumes for the network operators. In particular, we assume that MNO_1 has the maximum possible traffic load (i.e., $\rho_1 = 1$), while the rest MNOs have a common traffic volume ρ, which is a portion of the maximum load (i.e., $\rho_2 = ... = \rho_N = \rho \in [0, 1]$).

1) Telecommunication Metrics: Despite the importance of estimating the absolute values of throughput in the system, the deactivation of BSs potentially implies loss of connections. To that end, we consider the normalized throughput, which is an important GoS indicator that represents the percentage of served connections in the system. Fig. 9 presents the normalized throughput of the three infrastructure sharing schemes for different number of MNOs. In Fig. 9(a) ($N = 4$), we can see that all schemes guarantee the user service for variable traffic load conditions (i.e., $\rho < 0.8$). However, as the traffic volume grows, the R-bal, E-bal and R-to-1 approaches experience small losses (around 2% 3% and 5%, respectively), which still can be prohibitive for wireless cellular networks, while the proposed GTIS approach is able to guarantee the service of all the connections in the network. Hence, our scheme can guarantee the service of all connections for the case of $N = 4$ operators, which is highlighted as the most typical scenario in recent studies [5]. For higher number of operators, our proposal still outperforms the other three solutions and it guarantees the proper service in the network for traffic volume values up to $\rho = 0.8$ (case $N = 5$) and $\rho = 0.7$ (case $N = 6$). The degraded performance of the R-to-1 scheme is explained by the high number of deactivated BSs and the traffic service by one MNO only, whereas our approach proposes a distributed traffic roaming among the coexisting MNOs. In addition, we observe that GTIS achieves different performance with respect to the varying values of roaming cost, thus justifying once again the importance of this variable. For relatively small values of α (i.e., $\alpha = 0.1$), there are less active BSs and as a result the number of lost calls increases. However, compared to the state-of-the-art schemes, the GTIS supports higher traffic without losing any calls. For instance, in the case of $N = 6$ MNOs and $\alpha = 0.5$, the GTIS provides full traffic service, while R-bal supports up to $\rho = 0.6$, E-bal up to $\rho = 0.5$ and R-to-1 only up to $\rho = 0.2$.

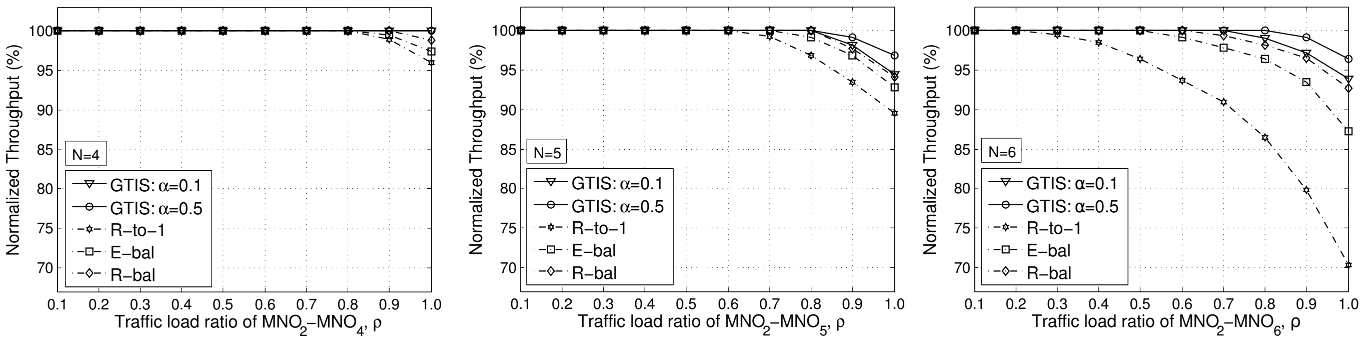


Fig. 9. Normalized throughput for (a) N=4, (b) N=5 and (c) N=6

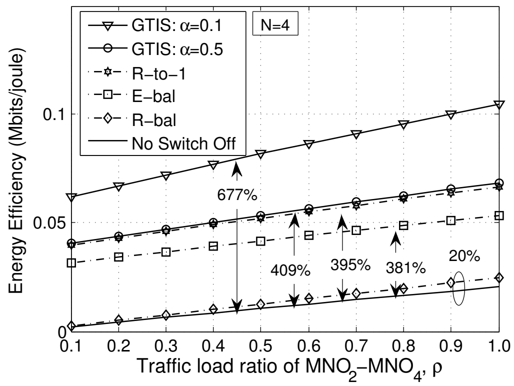


Fig. 10. Total network energy efficiency for different traffic profiles and variable roaming costs and comparison to the state-of-the-art schemes

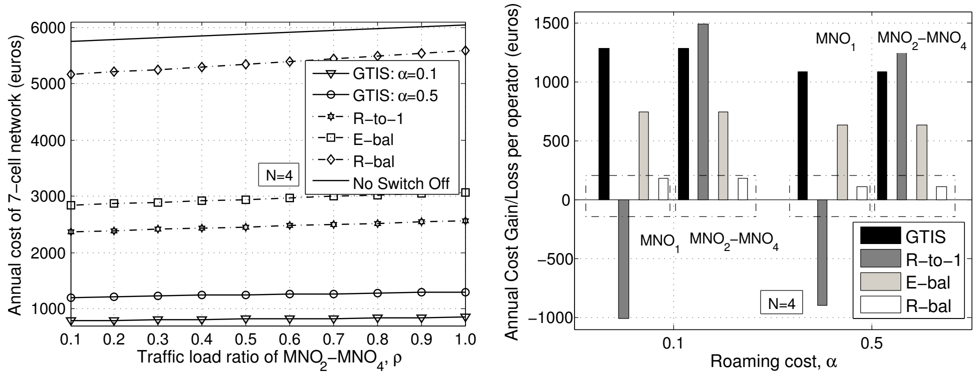
Fig. 10 presents the total network energy efficiency versus ρ for two different values of α and $N = 4$ operators. We observe that all schemes have the same behavior, since the energy efficiency increases with the traffic load. An important remark is that, for low roaming cost ($\alpha = 0.1$), GTIS significantly outperforms the baseline scenario (where no BS is switched off), as well as the three state-of-the art algorithms. However, for higher values of α, the energy efficiency gain of GTIS compared to the R-to-1 scheme gradually decreases and, eventually, the two schemes achieve similar performance for $\alpha = 0.5$. Even though the total network energy efficiency performance is the same, it is interesting to study the individual energy efficiency gains of the different MNOs. To that end, the individual gains for the specific (but representative) case of $\rho = 0.1$ and $N = 4$ are quantified in Table IV, where interesting conclusions can be extracted. In particular, independently of α, the R-to-1 scheme is beneficial only for the group of operators that switch off their BSs, while the operator with the active BSs faces important energy efficiency degradation. More specifically, the active operator is subject to higher energy consumption to serve the traffic of the whole network, while the rest operators theoretically achieve infinite energy efficiency, as they have their traffic served at zero energy cost. The proposed GTIS eliminates this unfairness, by guaranteeing energy efficiency gains to all operators, providing them with extra incentives to switch off their BSs by participating in the game. Comparing to the E-bal and R-bal that allow all MNOs to switch off their BSs for different time periods, the respective energy efficiency gains of the GTIS approach are clearly higher due to the lower number of active BSs.

2) Cost Metrics: The total network annual cost and the individual annual gains for the MNOs, having as a benchmark the No Switch Off scheme, are presented in Figs. 11(a) and 11(b), respectively. We observe that the total annual cost is not significantly affected by the traffic variations, since the fixed cost for the network operation is much higher than the cost due to the energy consumption in the network radio part. The corresponding values are also shown in Table III. In addition, for low roaming cost values ($\alpha = 0.1$), GTIS achieves a considerable reduction (around 86%) of the annual network cost, mainly due to the deactivation of many underutilized BSs. Regarding the individual revenue of each operator, plotted in Fig. 11(b), we may observe that, similar to the energy efficiency gains, the R-to-1 scheme provides financial gains only to particular MNOs, and more particularly for the MNOs that switch off their networks, whereas MNO_1 has higher expenses with respect to the No Switch Off scheme. On the other hand, for GTIS, all operators are able to have higher economic benefits compared to the E-bal and R-bal schemes, independently of the particular roaming cost value. Furthermore, as α increases, the GTIS achieves higher financial gains for the operators due to the increased roaming cost values.

Finally, Fig. 12 depicts the cost efficiency of the operators, which is a metric that provides an indication for the relation between the served traffic and the financial cost. In Fig. 12(a), we illustrate the individual cost efficiency with respect to different values of roaming cost. The traffic load in the network (ρ) has a great impact on the cost efficiency, which, on the other hand, is not significantly affected by the roaming cost (α) values. The cost efficiency increases with the lower roaming cost due to the reduced energy consumption. In addition, Fig. 12(b) presents the cost efficiency gains of the infrastructure sharing schemes, having as benchmark the No Switch Off scheme. The plot in Fig. 12(b) verifies our results so far, as it highlights the great difference in the R-to-1 approach between the active operator and the rest operators in the system. The proposal of switching off the whole network of the MNO with the lower traffic (R-to-1) results to great cost efficiency for $MNO_2 - MNO_4$, who do not consume any energy and are encumbered only with the compensation of the roaming cost to the active operator. Contrariwise, MNO_1 serves the whole traffic of the network and consumes significant energy, leading to an increased cost that is not compensated by the received roaming. GTIS overcomes this issue by providing cost efficiency gains to all operators, outperforming, at the

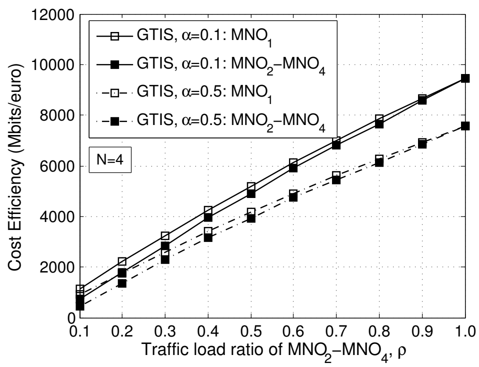
TABLE IV
OPERATOR ENERGY EFFICIENCY GAIN/LOSS WITH RESPECT TO THE NO SWITCH OFF SCHEME FOR $\rho = 0.1$

	$\alpha = 0.1$				$\alpha = 0.5$			
Algorithm	$\mathbf{MNO_1}$	$\mathbf{MNO_2}$	$\mathbf{MNO_3}$	$\mathbf{MNO_4}$	$\mathbf{MNO_1}$	$\mathbf{MNO_2}$	$\mathbf{MNO_3}$	$\mathbf{MNO_4}$
GTIS	93.2	27.1	27.1	27.1	94.2	45.3	45.3	45.3
R-to-1	-82.3	∞	∞	∞	-82.3	∞	∞	∞
E-bal	12.3	15.6	15.6	15.6	12.3	15.6	15.6	15.6
R-bal	11.9	13.2	13.2	13.3	11.9	13.2	13.2	13.2

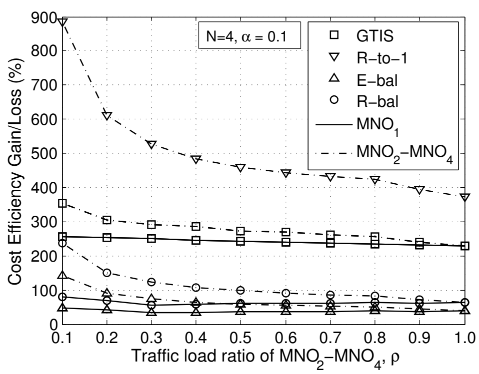


(a) (b)

Fig. 11. (a) Total annual cost for different traffic profiles and variable roaming costs and (b) Revenue for each MNO under variable values of roaming cost



(a)



(b)

Fig. 12. (a) Cost efficiency under different traffic profiles (b) Cost efficiency gain/loss versus No Switch Off

same time, the E-bal and R-bal schemes.

E. Discussion

Based on the analysis in Section VI-D, we have shown that the proposed GTIS outperforms the state-of-the-art approaches in terms of throughput, energy efficiency and annual network cost. In addition, it achieves balanced energy efficiency, cost gains and cost efficiency results for all the MNOs. Furthermore, through an extensive assessment, we have identified the significance of the roaming cost parameter, α. In particular, higher values of α achieve higher throughput. On the other hand, better performance results are attained in terms of energy efficiency, aggregate network cost, individual cost gains and cost efficiency, when lower values of α are chosen. Hence, the MNOs should choose the suitable value of α depending on their priorities. For example, if energy efficiency is not priority, each MNO could achieve better individual throughput performance by setting higher α. On the other hand, lower α leads to great energy efficiency gains for the network, whereas the individual performance of each operator is enhanced in terms of energy and cost gains.

VII. CONCLUSION

In this paper, motivated by the low BSs utilization during the night and the coexistence of multiple operators in the same area, we proposed a novel infrastructure sharing algorithm that encourages MNOs to share their resources and switch off redundant BSs. By employing game theoretic tools and realistic cost functions, we introduced a switching off scheme that allows the MNOs to reduce their expenditures in multi-operator cellular environments. The proposed scheme has been evaluated in terms of throughput, energy and cost efficiency for various traffic conditions and roaming cost values. The results have shown that our proposal can significantly improve the network energy efficiency, guaranteeing at the same time the network throughput in realistic scenarios of up to four MNOs. Regarding the financial costs/gains, the proposed scheme provides higher cost efficiency and fairness compared to the state-of-the-art algorithms, motivating the operators to adopt game theoretic strategies for their decisions. In our future work, we plan to elaborate on cooperative game theoretic schemes in order to investigate the potential trade offs.

VIII. ACKNOWLEDGMENTS

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Appendix A
Proof of Proposition 1

Based on Definition 2, we want to calculate the strategy s_i^* that minimizes the expected cost of player i. Furthermore, due to the game symmetry, all MNOs have identical switching off probabilities, i.e., $s_{i,m} = s_{j,m}$. By substituting these values in Eq. (7), we can obtain the strategy s^*, thus deriving Eq. (8). The roots of Eq. (8) correspond to the strategy of all players that minimizes the individual cost of each player. According to [26, Definition 3.4], a strategy profile $\mathbf{s}^* = \{s_1^* \dots s_n^*\} \in \mathcal{S}$ is the DSE if every element s_i^* of $\mathbf{s}^*$ is a dominant strategy of player i. In our case, the solution s_i^* of the game is:

$$\mathbf{E}[C_i](s_i^*, s_{-i}^*) \leq \mathbf{E}[C_i](s_i, s_{-i}^*) \forall i \in \mathcal{N}. \tag{28}$$

Hence, we derive a common strategy profile for all operators, i.e., $s_i^* = s^*$. Each element s^* is the dominant strategy for a given player, as it minimizes their expected cost, irrespectively of the strategies of the other players. Consequently, the solution, calculated in Eq. (8), is proven to be a DSE in our game.

Appendix B
Proof of Proposition 2

Given the symmetry of the game and by using the equality $s_{i,m} = s_{j,m} = s^*$, we will show that, under specific conditions and reasonable assumptions, the proposed game has a unique mixed strategy DSE. Each operator has as an upper goal to estimate its individual switching off probability that minimizes its cost. To that end, we calculate the roots of the partial derivative of the expected cost function with respect to s^*. Thus, we get Eq. (29) at the top of next page.

According to the Heine-Borel Theorem [32], if the cost function is concave (i.e., if its second derivative is always positive and its first derivative has opposite sign in the limits of the interval $[0, 1]$), there exists a unique solution to our problem. The second derivative of the cost function (Eq. (6)) with respect to s^* is given by Eq. (30) (top of the next page) and it is positive for the following realistic values: *i)* $N = \{2, 3, \dots, 6\}$, *ii)* $C_{const} \in [465.1, 598.3]$€, *iii)* $C_{tr}^{(m)} \in [4.8, 591.6]$€, *iv)* $C_{inc}^{(i,0)} \in [5.4, 613.1]$€, and *v)* $C_{roam}^{(m)} = \alpha \cdot \left(C_{const} + C_{tr}^{(m)}\right)$, with $\alpha \in [0, 1]$. The first derivative is an increasing function with a unique solution for s^* in the interval $s^* \in [0, 1]$.

Appendix C

In this appendix, we compare our non-cooperative approach to a centralized solution. In Fig. 13, we show the DSE for different number of MNOs, along with the global optimal solution (Pareto optimal), that represents the solution with the minimum expected cost. The DSE switching off probabilities result in low cost values that are very close to the optimal ones. In addition, it is worth noticing that the difference between DSE and Pareto optimal points varies with the number of MNOs. In particular, the presence of more MNOs leads to higher differences, thus requiring the precise calculation of the DSE in order to avoid higher costs. However, in most typical scenarios in European countries where no more than $N = 4$ operators are involved [5], our proposed formulation estimates accurate, close to optimal switching off probabilities.

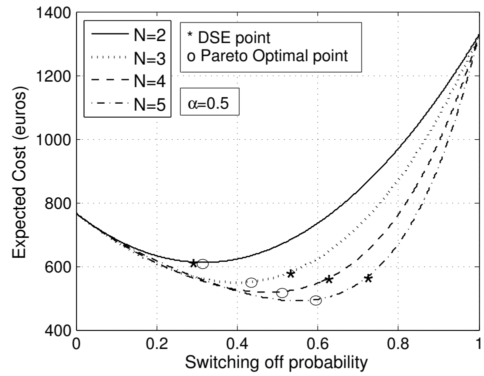

Fig. 13. The DSE point and the global optimal solution

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$$\begin{aligned}\frac{\partial \mathbf{E}[C_{i,m}]}{\partial s^*} &= 0 \Rightarrow N \cdot {s^*}^{N-1} \cdot C_{inc}^{(i,0)} + \left(\left(s^* + s^* \cdot (N-1) \cdot (1-s^*)^{N-2}\right) + \left(1-(1-s^*)^{N-1}\right)\right) \cdot C_{roam}^{(m)} \\ &+ \Bigg[\sum_{N_{ON}^{(m)}=1}^{N} \binom{N-1}{N_{ON}^{(m)}-1} \left(N-N_{ON}^{(m)}\right) (1-s^*)^{N_{ON}^{(m)}} {s^*}^{N-N_{ON}^{(m)}-1} \\ &- \sum_{N_{ON}^{(m)}=1}^{N} \binom{N-1}{N_{ON}^{(m)}-1} N_{ON}^{(m)} (1-s^*) {s^*}^{N-N_{ON}^{(m)}} \Bigg] \cdot \left[C_{const} + C_{tr}^{(m)} + \left(C_{tr}^{(m)} - C_{roam}^{(m)}\right) \cdot \frac{N-N_{ON}^{(m)}}{N_{ON}^{(m)}}\right]\end{aligned} \tag{29}$$

$$\begin{aligned}\frac{\partial \mathbf{E}[C_{i,m}]}{\partial s^* \cdot \partial s^*} &= 0 \Rightarrow N \cdot (N-1) \cdot {s^*}^{N-2} \cdot C_{inc}^{(i,0)} + (1-s^*)^{N-3} \cdot (N-1) \cdot (N-2) \cdot (1+(N-3)\cdot s^*) \cdot C_{roam}^{(m)} \\ &+ \sum_{N_{ON}^{(m)}=1}^{N} \binom{N-1}{N_{ON}^{(m)}-1} \cdot (1-s^*)^{N_{ON}^{(m)}-2} \cdot {s^*}^{N-N_{ON}^{(m)}-1} \cdot \Bigg[s^* \cdot N_{ON}^{(m)} \cdot \left(N_{ON}^{(m)}+1\right) \\ &+ \left(N-N_{ON}^{(m)}\right) \cdot \left(N-N_{ON}^{(m)}-1\right) \cdot (1-s^*) \cdot \left[C_{const} + C_{tr}^{(m)} + \left(C_{tr}^{(m)} - C_{roam}^{(m)}\right) \cdot \frac{N-N_{ON}^{(m)}}{N_{ON}^{(m)}}\right]\end{aligned} \tag{30}$$

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