Energy Efficient Infrastructure Sharing in Multi-Operator Mobile Networks

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Abstract

Network infrastructure sharing and base station (BS) switching off mechanisms have been recently introduced as promising solutions towards energy and cost reduction in cellular networks. Although these techniques are usually studied independently, their combination offers new alternatives to mobile network operators (MNOs) for serving their users and could potentially provide them with additional benefits. In this article, we introduce the concept of intra-cell roaming-based infrastructure sharing, where the MNOs may switch off their BSs and roam their traffic to active BSs operated by other MNOs in the same cell. Motivated by the coexistence of multiple operators in the same area, we present possible network deployments and architectures in current and future cellular scenarios, discussing their particular characteristics. In addition, we propose an innovative distributed game theoretic BS switching off scheme, employing an integrated cost function that takes into account all the different cases for a given operator to serve its own traffic (i.e., through active BSs of neighboring cells or exploiting intra-cell roaming-based infrastructure sharing). Finally, we demonstrate some indicative simulation results in realistic scenarios to quantify the potential energy and financial benefits that our proposed scheme offers to the MNOs in multi-operator environments, providing them with the necessary incentives to participate in the infrastructure sharing.

Index Terms

Infrastructure Sharing, Roaming, Game Theory, CAPEX, OPEX, Switching Off, Nash Equilibrium

I. Introduction

The deployment of 4G technologies, though in early stage, is changing the landscape in cellular networking. More specifically, a nearly 11-fold increase is expected for the global mobile data traffic in the next five years, reaching 15.9 exabytes per month by 2018 [1], thus compelling the mobile network operators (MNOs[1]) to extend their network infrastructure, in an effort to increase the network capacity and meet these pressing traffic demands. This rapid expansion of mobile cellular networks has become a major issue both for the society, due to the high energy consumption, and for the operators, due to the increased financial cost. In particular, the use of information and communication technology (ICT) across a wide range of applications currently accounts for 5.7% of the world's electricity consumption and 1.8% of global carbon emissions, something that translates into electricity bills in the order of $10 billion for the MNOs worldwide [2].

Network infrastructure sharing has been introduced as a promising viable solution for the MNOs towards the reduction of the capital (CAPEX) and operational (OPEX) expenditures, associated with the deployment and the operation of the cellular networks, respectively. This new paradigm, promoted by legal regulations that obligate the operators to install their antennas on the same buildings [3], embraces a set of strategies that enable the MNOs to use their resources jointly in order to reach their common goal, which is to guarantee customer service while achieving energy and cost reduction. From a technical perspective, infrastructure sharing can be classified into three categories with different levels of cooperation and control [4]: *i*) passive sharing, limited to the joint use of sites, masts and building premises among MNOs, *ii*) active sharing, where the MNOs share the active

[1]Please note that the terms "MNO" and "operator" are used interchangeably in this article.

network components such as antennas, switches and backhaul equipment, and *iii*) roaming-based sharing, where one MNO relies on the coverage of another MNO in a certain region on a permanent basis. Despite the technical challenges that might arise in such scenarios, the potential benefits of sharing part of the cellular network have been recently estimated up to €2 billion [5], further motivating the cooperation among different MNOs.

In the context of green cellular networking, the role of the macro base stations (BSs) and their contribution to the total energy consumption should be highlighted. More specifically, given the large number of deployed BSs (∼5 million worldwide) in conjunction with their relatively high operational power (∼1.7 kW), it may be concluded that approximately 80-90% of the total network energy is consumed to power the radio sites. However, cellular networks are dimensioned according to peak-hour traffic demands and, consequently, a portion of their resources remains unexploited during several hours per day, when the network traffic is low. These statistics have lately motivated the research community to shift towards the investigation of disruptive switching off schemes, in an effort to achieve drastic energy efficiency gains. The initial works on BS switching off considered clusters of cells with a single operator, where part of the BS infrastructure can be temporarily switched off, while the remaining active BSs can extend their coverage range in order to serve the whole network area. However, by exploiting the coexistence of multiple MNOs in the same area, it is possible to conceive a new promising sharing technique based on MNO cooperation: intra-cell roaming-based infrastructure sharing.

Intra-cell roaming-based infrastructure sharing extends the traditional roaming-based sharing basically in two ways: *i*) the sharing takes place in the same region, where the MNOs offer their mobile services, and *ii*) the sharing is dynamic (and not in a permanent basis), especially during low traffic periods. In addition, the involvement of various stakeholders (e.g., MNOs, trusted third parties, regulatory authorities, etc.) in future cellular environments entails a diversity of network architectures. As a result, additional challenges arise with respect to the BS switching off, since the conventional solutions are usually applied in plain hexagonal cellular scenarios, without considering the particularities resulting from the coexistence of multiple MNOs in the same geographic area.

In this article, our goal is threefold. First, we present some existing and future multi-operator network architectures, identifying their characteristics and the possible roles of the relevant stakeholders. Subsequently, we discuss the state of the art with respect to the BS switching off schemes in single-operator networks and we draw attention to the new challenges that arise in multi-operator environments. Finally, we introduce a game theoretic framework that enables the operators to take individual switching off decisions for their own BSs. 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 necessary incentives to participate in the game.

II. Multi-Operator Network Architectures

In this section, we present some of the possible scenarios (depicted in Fig. 1) and we briefly discuss the challenges and the traits of each particular case.

[Fig. 1 about here.]

A. Mobile Virtual Network Operators (MVNOs)

The spectrum and the network infrastructure in a given region are deployed and owned by a single operator (MNO_A in the example of Fig. 1(a)). All the other operators in the same area are virtual (MVNOs) and, since they do not own any spectrum or network infrastructure, they must lease resources from MNO_A in order to serve their clients. This model, also known as national roaming, has already been applied successfully in several countries thanks to its simplicity and its inherent advantages. In particular, the existence of MVNOs may be beneficial for the end-user, since it promotes the market competition, while, at the same time, the basic MNO in the area may capitalize the deployed infrastructure. On the other hand, it is uncertain whether this model can be compliant with the foreseen traffic demands in cellular networks, which probably cannot be met using only the existing infrastructure and the limited amount of resources. Moreover, the high spectrum prices make the operators reluctant to share their resources (and the market) with their competitors [6].

B. Trusted Third Party

The whole infrastructure in a certain area has been deployed and owned by an independent trusted third party, and the MNOs, who hold a spectrum licence, may enter into agreements for the employment of the access and core network (Fig. 1(b)). The main benefit of this model, which is gaining momentum in many countries (e.g., Spain [7]), is the significantly lower CAPEX for the MNOs, who are not concerned anymore for the maintenance of the hardware infrastructure, being also able to provide their services dynamically in a given geographic region. However, the lease of the network implies an increased OPEX, which in the long run may not be profitable for the MNOs. In addition, the expected participation of many MNOs in future cellular networks could potentially result in high leasing prices, raising additional barriers and challenges for the effective application of this model.

C. *Unique Infrastructure Provider*

There is one operator that has deployed the whole network infrastructure and leases part of it to other interested MNOs (Fig. 1(c)). This scenario is fueled by the fact that the same spots (e.g., rooftops) are usually appropriate for all MNOs and, consequently, an operator that has built out its network is able to capitalize on the potential interest of other MNOs on the specific location. In addition, this architecture can be considered as a hybrid model that combines some basic characteristics of the two aforementioned schemes, having though two main differences: i) the interested MNOs are not virtual, since they have their own spectrum license, and ii) the infrastructure owner is an operator and not an independent entity. In this case, the operator who provides the infrastructure is burdened with considerably high CAPEX and OPEX, which, however, can be depreciated through the efficient network leasing. From the perspective of the other MNOs, there is a tradeoff between the expected CAPEX (lower) and OPEX (higher), while it should be also taken into account that they rely on a competitive entity rather than a trusted third party. This architecture includes stakeholders with different levels of risk and profit, thus raising intriguing financial challenges, which require explicit models for the accurate analysis of each entity according to the different profiles.

D. *Standalone*

Various MNOs have deployed and run their own network in the same region (Fig. 1(d)). This model currently dominates in cellular networks, since it encompasses the lowest possible risk for the operators. Moreover, taking into account the rationality of the operators, along with the competitive nature of the telecommunications market, it is also very possible to appear in future architectures, especially in dense areas with high traffic. In this scenario, the MNOs have full control of their network, thus being able to estimate the expenses both for the network deployment and operation.

III. Base Station Switching Off and Infrastructure Sharing

In the previous section, we shed some light on the different sharing solutions that can be encountered in multi-operator networks. Nonetheless, regardless of the particular sharing agreement, the energy issue has always been in the spotlight of cellular networking, especially as the design and engineering of traditional cellular networks typically take place considering the peak traffic demands. As a result, an efficient joint resource allocation and network planning during low traffic periods (e.g., night zone) would allow the service of the traffic by a smaller number of active BS, thus enabling the deactivation of the remaining unused infrastructure. However, the decision of the particular BSs that should be switched off is not trivial, as it engages the end user satisfaction, which is of top priority for the telecommunication operators. In addition, this decision is even more complicated in multi-operator environments due to the conflicting interests of the operators and the diversity of the involved parameters. To that end, the design of BS sleeping mechanisms has recently become a very hot research topic, with the majority of the works focusing on the reduction of the network energy consumption, without compromising the provided quality of service (QoS) for the mobile users. In this section, we briefly discuss the state of the art on the BS switching off schemes in single- and multi-operator networks.

The core idea behind the works that deal with single-operator networks consists in the fact that a given MNO is able to switch off part of its infrastructure and extend the transmission range (by increasing the transmit power) of the remaining active BSs in order to provide coverage to the whole network. Several research attempts study the potential impact on the network performance of random [8] or specific [9], [10] patterns for switching off a subset of the BSs. These works focus rather on the spectral efficiency and the offered QoS (in terms of call-blocking probability) after the deactivation of the BSs, taking the reduced energy consumption for granted.

In addition, there are many works oriented to the switching off decision itself. More specifically, different criteria (e.g., traffic load [11], user spatial distribution [12] or network-impact [13]) are considered in order to identify the optimal BS switching off strategy, guaranteeing a certain level of user satisfaction in the network. In the same context, a very recent interesting approach is the application of reinforcement learning schemes that cope with the dynamic nature of the traffic load in current cellular networks [14] in order to overcome an important limitation of the existing works, which rely on past predefined traffic patterns based on the network history.

Despite their novelty and the promising energy savings, most works usually neglect the possible coexistence of the BSs, which offers to the MNOs the alternative of being served by other MNOs, collocated in the same area. Fig. 2 illustrates three possible cases for the cell operation in multi-operator environments, where each operator controls and operates its own BS (i.e., the architecture presented in Fig. 1(d)). In the simple case where all the BSs are active (Cell A), each operator is responsible for serving the traffic of its users. In case that all BSs have been switched off (Cell B), the active BSs of the neighboring cells (Cell A in the example) of each MNO can extend their range in order to prevent the generation of coverage holes. Finally, in case that only a subset of the BSs has been switched off (Cell C), their respective traffic can be roamed to the active BSs of the same cell.

[Fig. 2 about here.]

The aforementioned cases stress the need for new BS switching off mechanisms that consider all the contingencies in future networks. In their pioneer work [15], Marsan and Meo have proposed two interesting BS sleeping schemes for multi-operator environments: Roaming-to-One and Roaming-Balanced. In the former, only one BS remains active in every cell during low traffic conditions, serving the users of all operators, while, regarding the Roaming-Balanced scheme, the MNOs in a particular cell switch off their BSs for different portions of time in order to balance the expected financial expenses, associated with the roaming process. Although both schemes achieve noticeable energy savings, they neglect the possibility of switching off all BSs in a given cell and transfer the traffic to an active neighboring cell. In the next section, given the necessity for innovative solutions that take into consideration all the possible cases for cell operation along with the important parameters involved in future cellular networks (i.e., roaming and operational cost, energy consumption, QoS), we present a game theoretic switching off algorithm that enables the effective intra-cell roaming-based infrastructure sharing, providing significant gains to the participants operators.

IV. Game Theoretic Base Station Sleeping Mechanism

In a multi-operator environment, the involvement of multiple stakeholders with adverse interests and the different parameters that potentially affect the switching off decision (e.g., energy savings, roaming cost, traffic load, etc.) make game theory a suitable tool to study this problem. To that end, we introduce a novel game theoretic switching off scheme for the BSs in a multi-operator environment, taking into account the conflicts and the interaction among the different MNOs, as well as the different available courses of action.

We consider clusters of M cells (one central and $M-1$ peripheral cells), with N operators offering their services in each cell through different collocated BSs. The N BSs in the central cell always remain active in order to offer an extra alternative to the operators. More specifically, in case that all BSs in a peripheral cell have been deactivated and the intra-cell roaming-based infrastructure sharing is no longer possible, the MNOs are allowed to transfer the traffic load to the corresponding BS of the central cell. Therefore, the distributed network operation is further facilitated, enabling the modeling of the switching off decision process in the peripheral cells as a static non-cooperative game. The specific game theoretic formulation provides two important benefits. First, it is a distributed solution, applied by every operator individually in each peripheral cell, something that constitutes an important and practical feature in multi-operator environments, as the operators are not obliged to follow a specific centralized policy. The second benefit is that the proposed scheme does not require the exchange of excessive control information among the operators, since the BSs of the same cell should make their decisions without any communication among them.

The proposed game consists of N players (i.e., the MNOs in each cell) that have two possible actions (i.e., either remain on or switch off) and a cost function C that corresponds to the actual cost paid by each operator in every peripheral cell, including the cost of operation, roaming and power increase of the central BS. It is also worth highlighting the symmetry of the problem, as the participants (MNOs) have identical characteristics and the outcome of the game depends only on the selected strategies. Hence, by definition, the proposed game is symmetric, allowing us: i) to characterize it as game of complete information, as the players have a common cost function, ii) to formulate it with 2 macro-players (i.e., player A is a given MNO_i, while player B consists in the set of the remaining $N-1$ MNOs), and iii) to study the problem from the player's A point of view, generalizing the conclusions for every player.

Hence, considering the perspective of player A, four different cases can be distinguished:

- *Case 1 - Player A is ON - All operators in Player B are ON*: The total cost for the MNO under study includes the fixed operational cost for the BS (C_{const}) and the variable cost for serving its traffic (C_{tr}).
- *Case 2 - Player A is ON and a subset of operators in Player B are OFF*: In this case, the switched off BSs must roam their traffic to the active ones. In general, player A may serve, on average, $\overline{N}_{roam}$ BSs. Thus, the total cost of player A must take into account the increased operational cost for serving the additional traffic $\left(\left(\overline{N}_{roam}+1\right)\cdot C_{tr}\right)$, as well as the corresponding income from the roamed MNOs ($\overline{N}_{roam}\cdot C_{roam}$).
- *Case 3 - Player A is OFF and at least one operator in Player B is ON*: The operator under study does not have any operational cost, but it should pay the associated roaming cost (C_{roam}) to the active operator that serves its traffic.
- *Case 4 - Player A is OFF - All operators in Player B are OFF*: In this case, the cost paid by each MNO corresponds to the extra energy consumption for the power increase of the central BS (C_{inc}) in order to cover the area of a switched off BS.

The aforementioned cases can be summarized in the matrix representation of the game in Fig. 3. Having formulated the game in a strategic form, the next step is the identification of the stable states, which define the actions of the players. These states, also known as Nash Equilibria in non-cooperative games, provide the players with a certain payoff (resp. cost) that cannot be increased (resp. decreased) if they decide to unilaterally alter their decision. However, in real systems, selecting a pure action is not always feasible or fair. In our problem, for instance, the selection of a pure strategy, where only a specific subset of the BSs remains active (i.e., Cases 2,3), would require centralized control and coordination, while the deactivation of all BSs in all peripheral cells (Case 4) and the transfer of their traffic in the central cell might compromise the offered QoS in high traffic load scenarios.

[Fig. 3 about here.]

Therefore, to overcome this limitation, we study the problem in the mixed strategies domain, where each MNO_i selects a specific action with a certain probability. To that end, we define s_i as the probability of player A (i.e., MNO_i) to switch off its BS, whereas, the game's symmetry enables the grouping of the other $N-1$ operators (excluding MNO_i), assuming a common switching off probability s_j. Exploiting the strategic representation of the game, along with the switching off probabilities, we may derive the expected cost function for player A, as $\mathbb{E}[C] = f(s_i, s_j, N, Cost_k)$, where $Cost_k, k \in \{1, 2, 3, 4\}$ denotes the respective cost in each of the four different cases described above.

The probability that minimizes the cost function (i.e., the root of the equation $\frac{\partial \mathbb{E}[C]}{\partial s_i} = 0$) corresponds to the equilibrium of the game. More specifically, following this strategy, the players minimize their cost in a distributed manner, thus having no incentives to change strategy. Regarding the details of the expected cost function, as we may also observe in Fig. 3, four different costs are involved: i) the fixed cost for the BS operation (C_{const}), ii) the cost for serving the traffic (C_{tr}), iii) the cost for increasing the power of the central BS in order to serve the traffic of neighboring cells (C_{inc}), and iv) the cost for roaming the traffic to another operator in the same cell (C_{roam}). While the first three costs (i.e., C_{const}, C_{tr} and C_{inc}) are predictable and almost constant[2], C_{roam} can significantly vary, depending on the intentions and the demands of the operators. To that end, let us define $C_{roam} = a \cdot (C_{const} + C_{tr})$, with $a \in [0, 1]$ (as it does not make sense to have a roaming cost higher than the operational cost), and present some indicative Nash Equilibrium results in Fig. 4 in order to study the impact of N (number of MNOs) and a (roaming cost) on the switching off probabilities.

[Fig. 4 about here.]

Two main conclusions can be derived from Fig. 4. First, the NE switching off probabilities increase with the number of MNOs in each cell. In particular, as the number of coexisting operators in the same cell grows, MNOs have a stronger incentive to switch off their BSs and roam their traffic to other operators. Regarding the second basic observation, as expected, the switching off probability decreases for higher roaming cost, which is a prohibitive factor

[2]The traffic variations during night zone are negligible and, as a result, the C_{tr} can be considered constant.

for the BS deactivation. However, it is worth noting that the NE probability reduction is more intense in networks with few MNOs due to the risk of switching off all BSs in the cell. On the other hand, in networks with many MNOs, where the aforementioned danger is not so evident, the switching off probability for high a is still significant.

V. Quantifying the Gains

A. Simulation Scenario

We have developed a system-level C++ simulator for the network operation to assess the performance of the proposed infrastructure sharing scheme and quantify the expected gains in terms of energy efficiency and expenditures for the operators. The simulation scenario includes a typical urban 7-cell cluster (i.e., $M = 7$) of six peripheral cells and one central cell that always remains on. In each cell, N MNOs provide their services to a set of users[3], while we focus on the night zone where all operators have low traffic. Regarding the technical parameters, we assume a service rate of 64 kb/s and 256 kb/s for voice and data sessions, respectively, while we consider two different transmission power levels for the BSs, equal to 40 and 46 dBm for normal and extended operation, respectively. For the financial analysis, we assume $C_{const} \simeq 465$€, while the cost for the transmission and the power increase can take different values depending on the traffic level, i.e., $C_{tr} \in [5, 592]$€ and $C_{inc} \in [6, 613]$€. In addition, we have adopted a price of 0.1 €/kWh for the electricity charge and the roaming cost factor has been set equal to $a = 0.1$. In our experiments, we consider $N = \{4, 5, 6\}$ in order to study the impact of the number of MNOs in future networks.

To evaluate the performance of our scheme, we compare the proposed game theoretic infrastructure sharing strategy (referred as GTIS in this section) with two state of the art approaches [15]: *i*) the Roaming-Balanced (R-bal) scheme, where the MNOs switch off their BSs for different portions of time in order to balance their roaming costs, and *ii*) the Roaming-to-One scheme (R-to-1), where only the MNO with the highest traffic remains active and serves the total network traffic.

[3]Each operator serves 100 users, where the portion of data and voice users is 70% and 30%, respectively.

B. Performance Results

The normalized system throughput, defined as the percentage of the served users, is depicted in Fig. 5(a). As it can be observed, the proposed scheme guarantees the user satisfaction in the network in all cases, while the state of the art approaches experience losses in some scenarios. More specifically, as the number of MNOs increases in each cell, the network becomes overloaded and the deactivation of the BSs results in throughput degradation, as the infrastructure and the resources cannot be shared in an efficient way. As a result, in the case of $N = 6$, R-bal fails to satisfy approximately 2% of the network users, a percentage that can be prohibitive for wireless cellular networks. The losses are even greater in R-to-1 scheme ($\sim$10%) and, therefore, the service of the traffic in future multi-operator environments by only one BS in each cell cannot be considered as a viable solution.

[Fig. 5 about here.]

Fig. 5(b) presents the network energy efficiency achieved by the three schemes under study, considering topologies with $N = 4, 5$ and 6 operators. The first important observation is that, unlike the normalized throughput trend, the energy efficiency increases with the number of operators. More specifically, the high number of BSs in each cell implies high traffic and large energy consumption. Consequently, switching off schemes can contribute significantly in energy saving and the energy efficiency increases as most of the sessions can still be served by the active BSs. Even in the case of R-to-1 scheme in scenarios with $N = 6$ operators, the energy efficiency is extremely high, despite the throughput degradation, since the deactivation of five BSs excessively diminishes the energy consumption in each cell. The second noticeable observation concerns the pronounced energy efficiency gains of the proposed GTIS scheme compared to the R-bal algorithm in all scenarios. Although the two schemes exhibit similar performance with regard to the QoS, the GTIS enables the deactivation of more BSs, thus achieving up to four times higher energy efficiency.

Regarding the financial analysis, we focus on the case of $N = 4$ operators, which is one of the dominant scenarios in European countries [16]. The individual revenue for each operator that participates in the infrastructure sharing is plotted in Fig. 6(a), where we may observe that the R-to-1 scheme provides financial gains only to particular operators.

More specifically, only the MNOs that switch off their BSs can benefit from this scheme, while significant expenses burden the operator that undertakes the service of the total cell traffic by maintaining its BS active. On the other hand, adopting the proposed GTIS approach, all operators in the network achieve higher gains compared to the R-bal scheme, as the infrastructure is shared in a more integrated way. Finally, the total annual cost for the network is shown in Fig. 6(b). As it can be noticed, the difference in the network energy efficiency (Fig. 5(b)) is directly reflected to the financial cost. More specifically, the throughput guarantees provided by R-bal come at an increased energetic and economic cost, while GTIS reduces up to 77% this cost by deactivating an additional number of BSs, which are not necessary during low traffic periods. In any case, these results (i.e., throughput, energy efficiency and financial cost) should be jointly studied in order to decide the most appropriate switching off strategy that maximizes the operators gains without compromising the end-user service.

[Fig. 6 about here.]

VI. Conclusion

In this article, we discussed energy saving techniques in multi-operator cellular environments. Motivated by the coexistence of several MNOs in the same area, we introduced the concept of intra-cell roaming-based infrastructure sharing, which offers additional options to the operators for having their traffic served in regions where they decide to switch off their BSs. In addition, we proposed a novel game theoretic BS switching off scheme that enables the MNOs to achieve significant energy and, consequently, cost savings, by deciding distributively the deactivation of their BSs in a given cell. The simulation analysis showed the potential gains of the proposed scheme in terms of energy and financial cost, providing the operators with the necessary incentives to participate in the network infrastructure sharing. Finally, it is worth mentioning that the foreseen massive small cell deployment in next generation networks is expected to have a key role in the design of effective infrastructure sharing and switching off schemes, something that will be addressed in our future research.

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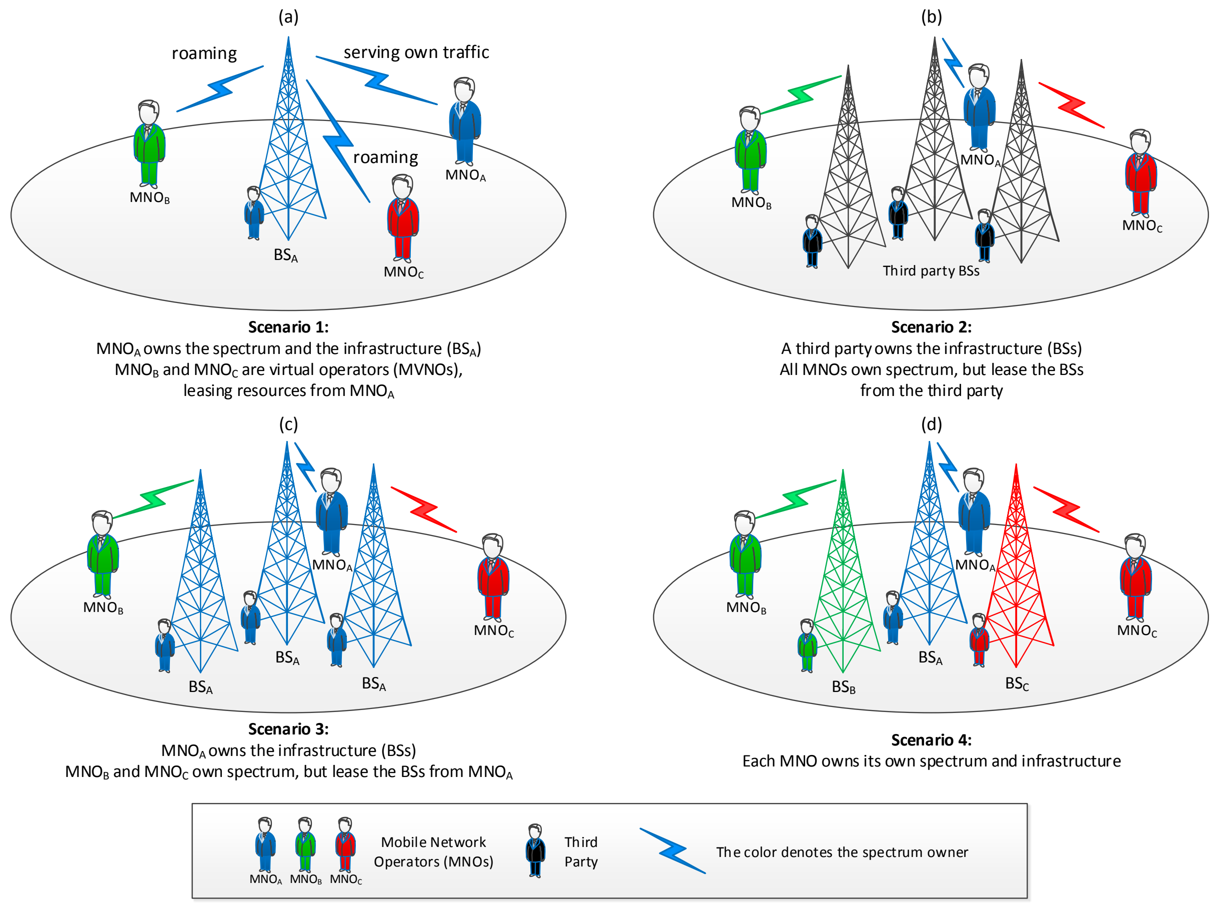


Fig. 1. Multi-Operator Cellular Network Architectures

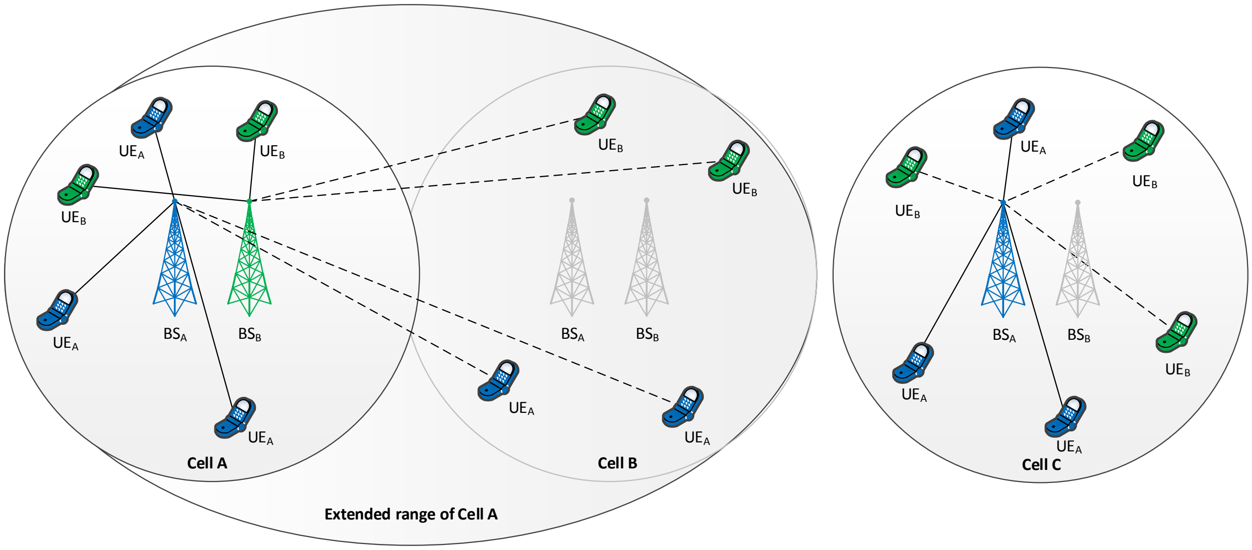


Fig. 2. Possible Cell Operations in Multi-Operator Environments

		Player B: N-1 MNOs (excluding MNO_i)	
Player A: MNO_i	*Actions*	Remain ON	Switch OFF
	Remain ON	$C_{const} + C_{tr}$	$C_{const} + (\overline{N}_{roam} + 1)C_{tr} - \overline{N}_{roam}C_{roam}$
	Switch OFF	C_{roam}	C_{inc}

Fig. 3. Cost Matrix of the Proposed Game

Roaming cost coefficient

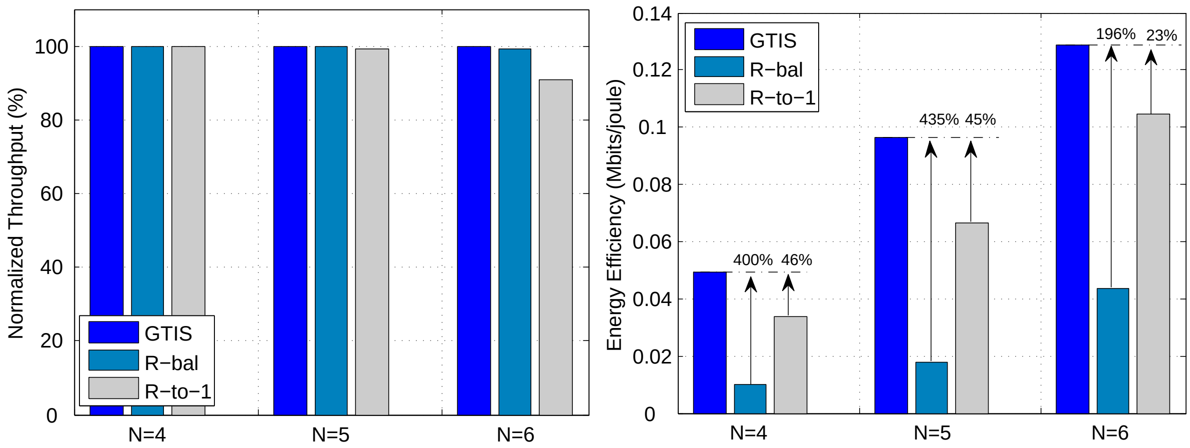
Number of MNOs

N	α = 0.1	α = 0.3	α = 0.5	α = 0.7	α = 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

As N increases, MNOs have a stronger incentive to switch off their BS and roam their traffic to other operators

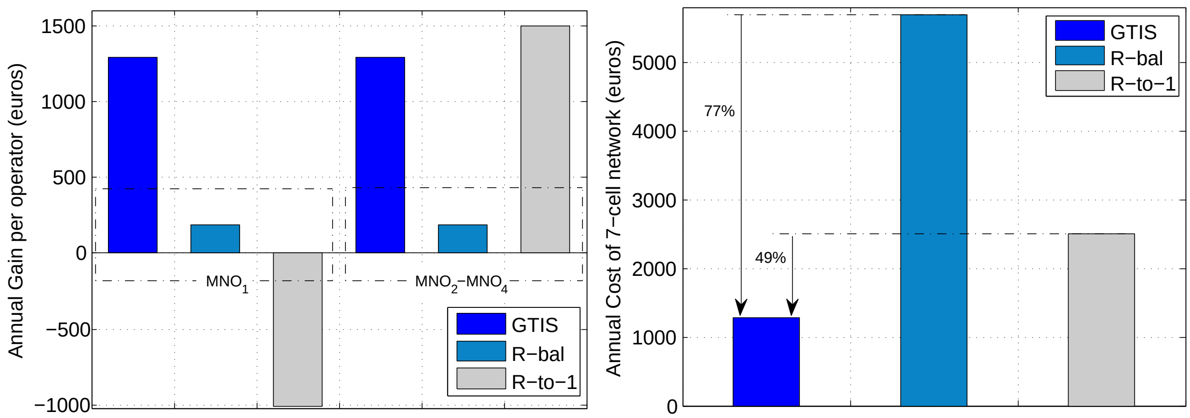
As α increases, the additional cost for traffic roaming discourages MNOs from switching off

Fig. 4. NE Switching Off Probabilities



(a) Normalized Throughput (b) Energy Efficiency

Fig. 5. Network Performance Metrics vs. Number of Operators ($N = 4, 5, 6$)



(a) Individual Annual Gains per Operator (b) Total Annual Cost per Network

Fig. 6. Annual Financial Data for Networks with $N = 4$ Operators