Saving Energy Through National Roaming: A New User Association Scheme

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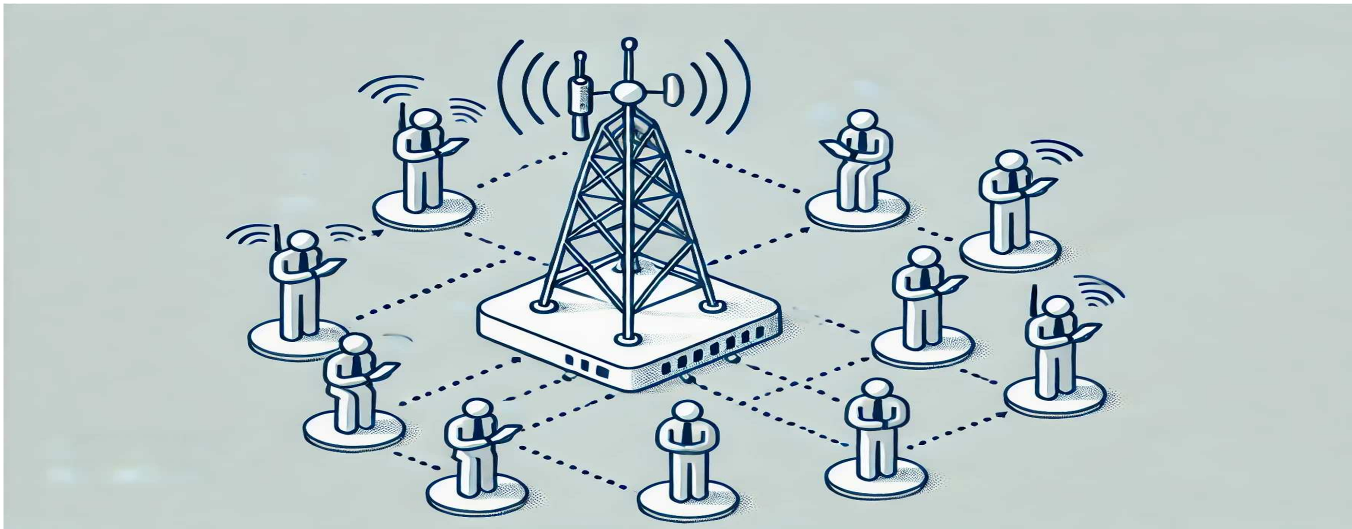

Fig. 1. Cellular Network Representation - Users and BS

As a result of the rollout of new technologies like 5G and a rise in demand for mobile data and connectivity, Mobile Network Operators (MNOs) need to operate efficiently and sustainably while considering energy prices and operational costs into account. Nevertheless, MNOs face challenges in maintaining service quality and running their applications efficiently. In this paper, we will investigate the potential energy-saving opportunities in cellular networks through inter-operator collaboration, focusing on National Roaming (NR) between MNOs. This collaboration involves sharing infrastructure and dynamically managing network resources to reduce power consumption and operational costs while improving the quality of service (QoS). The research addresses key research questions about NR's benefits and challenges, its impact on users, and power consumption. Ultimately, we propose a user association scheme that aims to reduce power consumption while considering user requirements with a focus on energy efficiency (EE). These evaluations are carried out by performing a case study on Dutch Cellular Networks using publicly available data and simulations to model various scenarios. The results revealed that National Roaming can improve user satisfaction and lower power consumption compared to the no-cooperation scenario between operators. More specifically, when employing our user association scheme, we observed a reduction of 27.78% in power consumption while maintaining better QoS where the fraction of the satisfied population is increased by 28.67% compared to no-cooperation.

Additional Key Words and Phrases: Cellular Network, Inter-operator collaboration, User Association Scheme, Power Consumption, Simulation

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1 INTRODUCTION

The demand for mobile data and connectivity has gone up significantly in today's digital world, driven by the increasing number of IoT devices and the launch of new technologies such as 5G. As a result, cellular networks need to operate smoothly and effectively. Mobile Network Operators (MNOs) face challenges to ensure that their networks operate effectively and maintain high levels of quality of service (QoS). As the demand for connectivity continues to rise, so does the energy consumption of cellular network operations. The increase in the demand for data traffic can have a significant impact on the costs of running a mobile network, mainly due to a potential increase in energy consumption. This problem is exacerbated by the recent increase in energy prices in the EU [4]. As a result, strategies with a focus on power and energy savings are of great interest to MNOs. One of the possible strategies is a nationwide inter-operator collaboration also known as "National Roaming" [7]. In this scenario, the user can be served by any available MNO. This sharing method is the most cost-efficient principle for any emerging market and can be considered the best approach for technology consolidation and migration [6]. Besides, it allows operators to adjust their resources to the demand as network traffic or user density changes over time without experiencing a major increase in energy costs. For instance, Mobile Network Operators can share their infrastructure and make collaboration arrangements to reduce power consumption [3]. This may bring some benefits such as an improvement in environmental sustainability and reduction in operational costs. Furthermore, users may benefit from this collaboration through enhanced service and expanded network coverage. Considering these aspects, this paper aims to investigate aspects of this collaboration, with a focus on National Roaming in the context of cellular networks. This work will be guided by the following research questions: (i) How inter-operator collaboration, specifically National Roaming, reduce power consumption and enhance efficiency in cellular networks? Is this collaboration advantageous for all included sides like users and MNOS? (ii) How the existing user association schemes can be improved by considering primarily the power consumption and its impact on energy saving and efficiency? (iii) What is the impact of integrating a more accurate power consumption model in the potential energy reduction of national roaming? By addressing these research questions, this paper aims to provide some insights into the energy-saving opportunities inherent in collaborative cellular networks, while also identifying its potential challenges and trade-offs. The analysis and findings in this paper can help MNOs and policymakers to make decisions in the context of cellular networks.

2 NATIONAL ROAMING

National roaming is an infrastructure-sharing strategy that allows mobile network operators (MNOs) to utilize each other's infrastructure when necessary [10]. Nowadays, some countries are using national roaming as a sharing strategy [3]. Despite having numerous advantages, regulatory concerns make its implementation challenging in some countries. In the following subsections, these challenges and benefits of national roaming will be discussed from the perspective of the two main stakeholders: MNOs and users.

2.1 Mobile Network Operator Perspective

National roaming can enhance efficiency in several ways. For instance, by providing stable and consistent connectivity, optimizing network performance through better coverage, higher data rates, and improved connections. While NR brings some benefits, it also presents challenges for Mobile Network Operators (MNOs).

2.1.1 Benefits. Higher signal quality can be achieved by letting each user connect to the BS offering the highest signal quality and potentially decreasing the power consumption [9]. Furthermore, sharing a bill with other MNOs leads to a potential increase in income. In this way, MNOs can increase their service quality and coverage by implementing new technologies or setups and they may attract more users, thereby increasing market share and revenue. Sustainability is a key consideration for both MNOs and countries. To achieve sustainability goals, energy and resource efficiencies are two of the main requirements that need to be fulfilled. One of the main technology trends for energy and resource efficiency is resource sharing in terms of physical infrastructure sharing and spectrum sharing [4]. MNOs can share infrastructure such as BSs, and antennas, which reduces the need for each MNO to operate and maintain their infrastructure. This reduction in the number of base stations mitigates the need for an extra installation, particularly in rural areas. Since each base station demands power for its operations, including the antennas and cooling systems, when the sharing is done, the overall energy/power consumption can be reduced. Furthermore, national roaming allows for dynamic resource management, enabling MNOs to adjust their base station operations based on real-time data. During off-peak hours, MNOs can arrange the network traffic onto fewer base stations and turn off the ones that are not actively used [1]. With this, energy can be saved and also it may increase the lifetime of the infrastructure components by ensuring power is consumed only when and where needed.

2.1.2 Challenges. Implementing national roaming might be difficult due to the potential decrease in operator revenues. To address these challenges, considering sharing only the infrastructure among certain operators, specific radio types, or in certain areas (such as Rural Access Networks) [10] could be beneficial. In general, the main challenges of MNOs collaboration are related to spectrum sharing and support of the network elements/resources [4]. Although the spectrum sharing and support of the elements/resources may offer significant opportunities in the efficiency and coverage of cellular networks, they may introduce challenges related to interference management, security and privacy issues, and technological challenges. For instance, since each MNO has different user demands and network configurations, minimizing interference requires complex systems and algorithms that might be hard to implement. And, some of the MNO's BS may have a higher load which can lead to performance degradation or equipment failure.

2.2 Users Perspective

National roaming offers both advantages and disadvantages to users. Although it improves the QoS and connectivity, it also presents some problems related to costs, service quality, and data security.

2.2.1 Benefits. Improved network coverage is particularly beneficial in rural or remote areas where some operators may have weak signals. By accessing multiple networks, users can experience higher signal quality and better connectivity, leading to more reliable and consistent connections. Furthermore, NR can help to ensure that the user is connected without interruption, which leads to an improvement in the quality of service.

2.2.2 Challenges. A user might encounter higher costs when roaming on another network due to the unavailability of their home network. Additionally, QoS rates can vary depending on the available sharing agreements and the performance, leading to potential issues such as low data rates and intermittent connections. Moreover, the privacy and security concerns are other important aspects. Since users connect to different networks, this situation might increase interceptions and vulnerability to cyber-attacks.

2.3 Benefits and Challenges for All Included Parties

In summary, MNOs with denser deployment may financially benefit due to serving a large number of customers, but the competition among operators could result in higher prices for users. Imbalances in certain areas may end up with degraded quality of service, so some users might switch their networks to another operator thus impacting MNOs' market position and revenue. Furthermore, in some cases, the necessary signal quality and data rate may fall below the minimum threshold which leads to a decrease in QoS and this is an undesirable situation for the operators. For instance, suppose customers of MNO1 are roamed to MNO2, in this case, MNO2 may experience some advantages and disadvantages. Advantages include increased revenue, network utilization, and market positioning, while disadvantages may include network capacity issues and increased costs. As a result, NR's impact varies across stakeholders, offering both opportunities and risks for MNOs and users.

3 POWER CONSUMPTION MODEL

To understand the potential benefits of national roaming in terms of energy savings, we need to model power consumption as accurately as possible. For this, we use the simulator in [10] and develop a more accurate power consumption model using the existing disaster-resilience simulator [1]. Base station sleep mode, amplifier efficiency integration, and all other components that may contribute to the total power are added and will be explained in the coming subsections. The total power consumption of cellular networks consists of transmission power, digital signal processor unit power, air conditioning unit power, and microwave link power (backhauling) [8]. For the antenna transmission power, the amplifier efficiency needs to be taken into account. The amplifier efficiency shows how efficiently the amplifier converts power into RF power that is transmitted by the antenna. In real-world cases, power amplifiers are not 100% efficient, so amplifiers can not convert all DC power into RF power. To consider this inefficiency, the calculated transmission power needs to be adjusted, accordingly. Transmission power affects the QoS, signal strength, and area that the signal can cover. And, it has a direct relation with power consumption. In the coming subsections, we will give more details about the sleep mode, backhauling, and array antennas.

Table 1. Constant Power Components

P_{sleep}	75 W
P_{mlink}	80 W
$P_{\text{rectifier}}$	100 W
P_{dsp}	100 W
$P_{\text{transceiver}}$	100 W
P_{aircond}	225 W
PA_{eff}	12.8 %

3.1 Base Station Sleep Mode

The sleep mode is applied to increase energy efficiency in cellular networks. When no user is connected to a specific BS, the power consumption of the BS needs to be considered. Since, when the BSs are in sleep mode, they still consume some power [8]. In our model, we assume that this power consumption is 75 W, as indicated in Table 1.

3.2 Backhauling

In the context of cellular networks, backhauling refers to the communication between base stations and the core network. In our power consumption model, a microwave link is assumed for backhaul. The role of the link is to help connect base stations to the core network and support high data rates in transmission. The authors of [2] assumed that the consumption of the microwave link is a constant value. Although in practice the power consumption of the microwave link increases linearly with the data rate D and is dependent upon the transmitted data rate, for simplicity we also assume constant power consumption for backhaul transmission.

3.3 Number of sectors (Array Antennas)

Each cell is divided into a number of sectors, and each sector contains an array of antennas and some other types of equipment. The components in the table 1 can be divided into different groups. The power amplifier, transceiver, digital signal processing unit, and rectifier are used per sector, so the power consumption of these components needs to be multiplied by the number of sectors [2]. Due to the fact that each sector may function independently and consume power separately, this should be taken into account in order to have an accurate model. In the model, we assumed that the number of sectors as 3 since this is the common number for macrocell base stations.

3.4 Total Power Consumption

The complete formula for the total power consumption can be seen in the equation 1. First of all, the components shown in table 1 can be separated into two groups: load-independent and load-dependent. Load-independent components are $P_{aircond}$, P_{mlink}, and $P_{rectifier}$ and load-dependent components are P_{dsp} and $P_{transceiver}$. Load-dependent components can be multiplied by the load factor to have a more accurate model [2]. The ratio of the amount of base station capacity used at any particular moment is represented by the load factor. For simplicity, the load factor can be determined by the ratio of the current power to the maximum power of the base station. Furthermore, P_{tx} and P_{pa} depend on the network load, so they vary based on the number of active users and the required QoS.

$$P_{total} = P_{loadind} + (P_{loaddep}) * L_{factor} + P_{tx} + P_{pa}, \tag{1}$$

where P_{tx} is the transmission power, L_{factor} is the load factor, $P_{loadind}$ represents the power consumption of the load independent components and $P_{loaddep}$ is the power of the load dependent components. By taking into account the inefficiency in the power amplifier, the power consumption of the amplifier can be determined using the following equation:

$$P_{\text{pa}} = P_{\text{rf}}/P_{\text{eff}}, \tag{2}$$

where P_{pa} is the power consumption of the power amplifier, P_{rf} is the desired RF power level, and P_{eff} is the amplifier efficiency. Table 1 shows the constant power values that were used. These values are obtained from [2] and used for the total power consumption model. The definition of each component can be seen below. P_{sleep} is the power consumed when the base station is in sleep mode, P_{mlink} the power of the microwave link transmission, $P_{\text{rectifier}}$ is the power of the rectifier, P_{dsp} the power of the digital signal processor, P_{aircond} is the power of the air conditioning unit and PA_{eff} is the efficiency of the power amplifier. Components that have fixed power values such as P_{dsp}, P_{aircond}, and P_{mlink} depend on the base station and transmission power depends on the channel. Furthermore, we are not distinguishing between co-located BSs, and therefore the P_{aircond}

[1] The modified simulator can be found at https://github.com/ataberkclb/disaster-resilience.

is calculated per BS regardless of having another one sharing the same physical location.

4 USER ASSOCIATION SCHEME

A user association scheme defines how users or mobile devices are connected to base stations within the network. Many user association schemes have been proposed by research papers already [5]. However, our goal is to propose an inter-operator user association scheme that aims at reducing power consumption with acceptable quality of service (QoS) requirements. In the scheme, users are associating not only to their own MNO infrastructure but also considering other MNOs in the user association. The explanation of the algorithm for the user association scheme can be found below.

As a starting point, the user association scheme from [10] is used for the initial connection. Firstly, it is assumed that no previous connections between users and BSs are made. Each user is identified by their coordinates. For each user, the algorithm considers all base stations and calculates the required transmission power for each user and BS link, and determines the best BS that gives the lowest power needed with the highest SINR to establish a connection. Furthermore, if it's needed the transmission power is adjusted to meet the SINR requirements of associated users while minimizing power consumption. This ensures that users are connected in the best possible way in terms of signal quality and data rate. After this initial association, the checking process of the number of users connected to each base station is made. BSs are sorted in ascending order based on the number of connected users. This sorting mechanism allows for redistribution of users from loaded BSs to less loaded ones leading to efficient power usage and optimization in the network performance. Also, BSs with few connected users are turned off in order to improve overall performance and further decrease in power consumption. Otherwise, there might be some BSs that are overloaded which leads to a decrease in QoS and signal quality. Furthermore, if any BSs have fewer users than the threshold, those users are reassigned to other base stations that have the highest SINR and that meet power requirements. Lastly, the algorithm performs iterative optimization to refine power levels and user associations such as power adjustments, recalculating of SINR [3], bandwidth allocation, etc.

The transmission power does not solely depend on the distance between the user and BS. There might be a base station somewhere else that gives better results in terms of power consumption. So, the required transmission power [8] for each BS needs to be taken into account to maintain the desired SNR and QoS requirements. And, the user can be connected to the BS that requires the least power while ensuring QoS requirements. These adjustments can be made based on the load on the BSs and the number of connected users. Furthermore, when users are connected to the BS, they may share the available bandwidth with the existing user which may affect the QoS. In order to prevent this, bandwidth allocation can be made based on data rate and channel conditions. The required bandwidth for each user can be determined based on data rate and spectral efficiency (SE) as shown in the equation [5]. Bandwidth allocation needs to be done proportionally among users in a channel and if it exceeds the total BW, scaling needs to be done. Lastly, interference calculation [7] for each user can be used for adjusting the transmission power from all neighboring BSs.

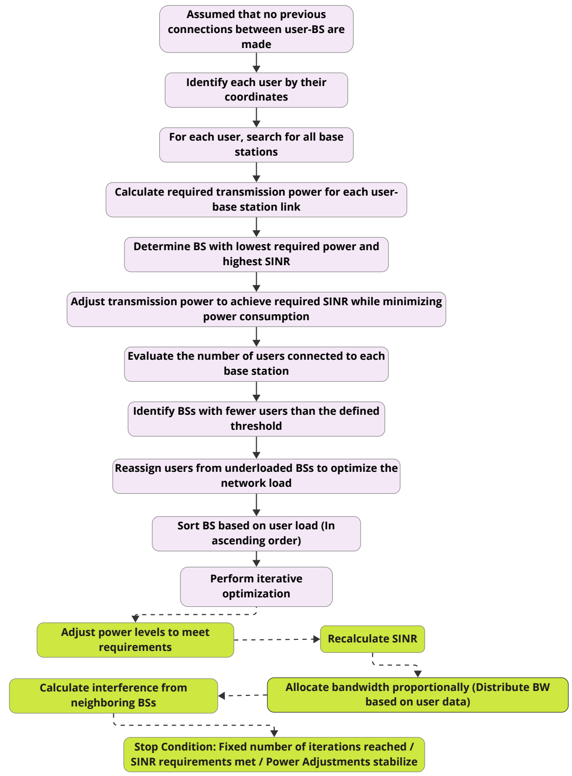


Fig. 2. User Association Scheme Diagram

SINR (Signal to Interference and Noise Ratio) helps to find the optimal BS and user link. In the scheme, the user connects to the BS that gives the highest SINR which minimizes the FDP and maximizes the FSP. And, higher SINR leads to better signal quality and quality of service. SINR in dB can be calculated by:

$$\mathrm{SINR} = P_{\mathrm{tx}} - \mathrm{PL} + G_{\mathrm{antenna}} - N - I, \tag{3}$$

where P_{tx} is transmission power, Gantenna the antenna gain, PL the pathloss, N is the noise power, and I the interference power. Bandwidth Allocation can be done by calculating the SE, required BW, and capacity for each user. Spectral efficiency (SE) is a measure of how effectively the available bandwidth can be used for data transmission and can be calculated as:

$$SE = \log_2(1 + \mathrm{SINR}). \tag{4}$$

To ensure the total allocated bandwidth does not exceed the channel's capacity, the required BW can be adjusted. The required bandwidth can be calculated from:

$$Required_{BW} = \frac{DataRate_{Requirements}}{SE}. \tag{5}$$

Capacity for each user can be found from:

$$C_i = B_i \cdot \log_2(1 + \mathrm{SINR}_i), \tag{6}$$

where B_i is the bandwidth allocation for user i, $SINR_i$ is the SINR per user. Interference from neighboring base stations affects the transmission power required to maintain the desired SNR. So, in order to minimize this interference, transmission power and bandwidth allocation need to be adjusted. The interference can be calculated from:

$$I = \sum_{j} \left(P_{\text{tx},j} \cdot PL_j^{-1} \cdot G_{\text{antenna},j} \right), \tag{7}$$

where $P_{tx,j}$ is the transmission power of the base station j, PL_j is the pathloss from base station j to the user i and $G_{antenna,j}$ is the gain of the antenna at base station j. The power that each BS needs to have to maintain the QoS requirements and necessary signal strength can be calculated as:

$$P_{\text{req}} = \frac{\text{SINR}_{\text{min}} \cdot (N + I)}{G_{\text{antenna}} \cdot \text{PL}}. \tag{8}$$

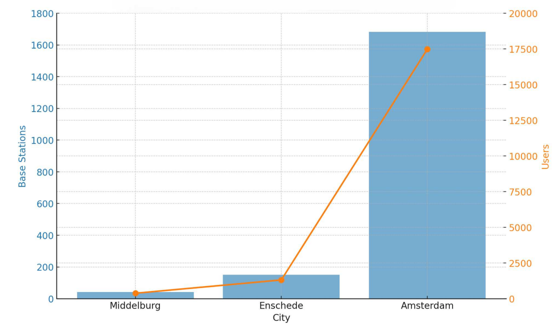
Furthermore, it can help to ensure that each BS transmits with enough power without excessive usage.

5 RESULTS

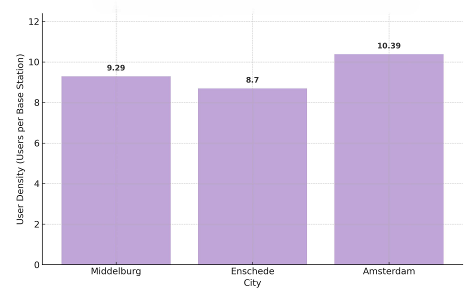
In cellular networks, different inter-operator collaboration methods among mobile network operators can impact metrics such as FSP (fraction of satisfied population), FDP (fraction of disconnected population), and total power consumption. By analyzing these metrics, the performance of the operators and a comparison between the sharing strategies can be made. The plots shown below demonstrate the comparative analysis of network performance between two scenarios: "No Cooperation" and "Full Sharing" among MNOs. In this paper, full sharing refers to the scenario where all BSs from all MNOs are treated as being part of a single MNO for the user association purposes. For instance, a user can be connected to any available BS regardless of their home network operator, while no cooperation refers to the scenario where a user can only connect to its own MNO BSs. The analysis focuses on the following key parameters: Fraction of Satisfied Population (FSP), and Total Power Consumption across Enschede.

The number of users and BS, and user density per city can be found in Figure 3a and Figure 3b, respectively. Figure 3a shows the total number of users per BSs from all MNOs which may influence the network performance and efficiency. These metrics have an impact on user satisfaction and power consumption. Higher user density results in higher power consumption due to, e.g., the increased data rate transmission. Analyzing these graphs can be helpful to implement methods like setting BSs to sleep mode in low-demand areas which can reduce power consumption. Furthermore, the load distribution can be made accordingly by considering user satisfaction and quality of service. In this case, Amsterdam has the highest user and base station compared to other regions. This may conclude that efficient inter-operator collaboration applications might be difficult and complex for Amsterdam. Nevertheless, there might be some potential benefits in this case. For instance, with the balanced and fair competition between operators, technological developments can be implemented and since user density is high, operators might focus on these areas more, and with advanced network management, better QoS and signal quality can be achieved.

Simulation is tested with the proposed user association scheme and the new power consumption model. Figure 5 is a result of full sharing and no cooperation.



(a) Number of Users and Base Station per City



(b) User Density

Fig. 3

Figure 4 shows the percentage of users being served by each MNO when the proposed user association scheme is being used. In Enschede, there are around 3939 users in total, under the assumption that 2% of the population is active users. From which 32.5% are being served by MNO1, 42.4% by MNO2 and 15.4% by MNO3. It can be seen that most of the users are connected to MNO2 followed by MNO1. MNO3 has the lowest user percentage and this might be because of the coverage area and capacity of this operator. However, MNO2 experiences a high serving percentage to MNO3, which is 39.4%, and MNO1 serves their 34% of users to MNO3 showing that a significant part of their users are served by MNO3. This is aligned with the results we have. From Figure 5, it can be seen that with the full sharing, MNO3 has the highest FSP and lowest power consumption, so most of the users of MNO2 connect to MNO3 since they might benefit more from that operator related to the proposed user association scheme.

With the full sharing, the user can connect any BS with the best QoS, and the overall user experience is enhanced. Since the user connection can be made regardless of MNO indicating that users are not limited to specific MNOs infrastructure, the QoS is consistent across different geographical areas. From 5a, it can be seen that MNO2 has the highest FSP, indicating that most of the users of this operator are satisfied according to QoS and data rate requirements in the no cooperation case. With the full sharing, FSP values are higher for all MNOs which indicates that by cooperation among

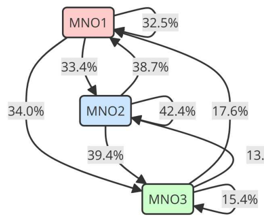


Fig. 4. User Transition Between MNOs

MNOs, user satisfaction and service requirements can be enhanced a lot.

Furthermore, MNOs share their infrastructure and base stations with others which leads to less active BSs in the network leading to reduce in the total power consumption. And, the network traffic can be distributed across the shared infrastructure which may prevent base stations from being overloaded so the resources can be used more efficiently. Also, from Figure 5b, with the no cooperation scenario, the power consumption is way higher, which shows that independently working of MNOs leads to higher energy usage. With the full sharing, consumption is significantly lower across most of the MNOs, indicating less energy usage and better energy efficiency. For the MNO2, it can be seen that with the full sharing the power consumption is higher than the no cooperation case. This might be because of the uneven distribution of users and can be concluded from Figure 4. In Figure 4, most of the users connect to the MNO2s base station due to the better QoS and signal quality, this may increase the load in the network of MNO2 so the power consumption can be increased in this case.

Figure 6 shows the power levels of channels for each BSs before and after the reallocation process in the user association scheme. It can be seen that the reallocation process of users decreased the power consumption in the no-cooperation scenario. Also, it can be observed that load has been distributed more evenly across the BSs which results in enhanced network performance and efficiency. Furthermore, by comparing plots with the proposed user association scheme is applied which is 5b and without the new user association scheme 7, it's clear that there is a reduction of 18% in power consumption for the full sharing and reduction of 24% for the no cooperation scenario by applying the proposed user association scheme.

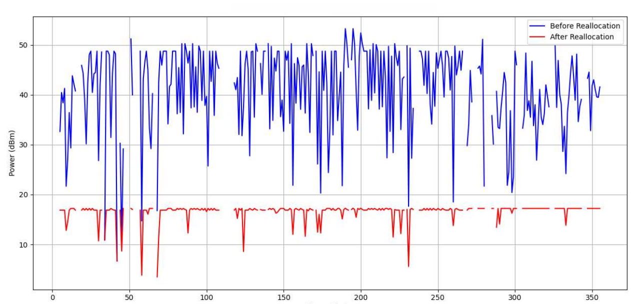
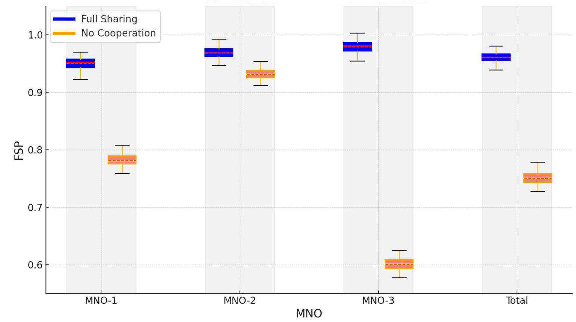
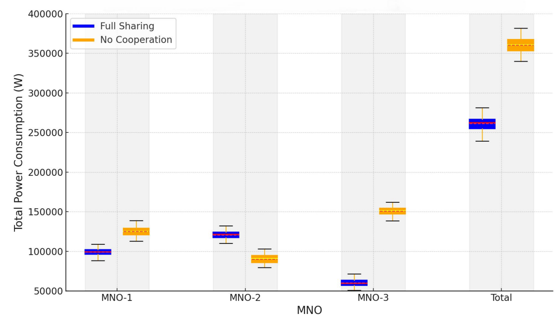


Fig. 6. Power Changes Before and After Reallocation Process



(a) FSP



(b) Power Consumption

Fig. 5. Performance Comparison - Enschede

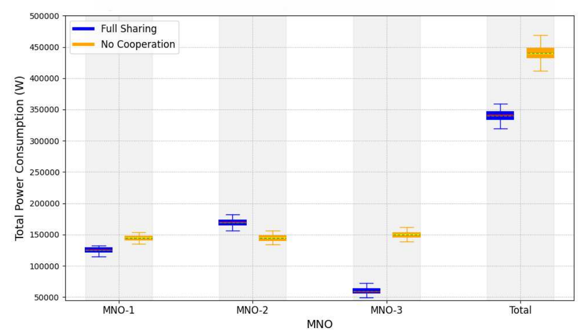


Fig. 7. Power Consumption Results Without Proposed User Association Scheme

6 DISCUSSION AND LIMITATIONS

Implementation of NR may present some challenges for users and MNOs as explained in section 2. There are some possible ways to overcome these challenges for all included parties/sides when the NR is implemented. Users should not be charged extra costs in case of opportunistic roaming. Making agreements between municipalities or stakeholders with operators might solve these issues. Competition among MNOs might be beneficial for operators such as development in technological equipments or better price offers for users but in general this results in less QoS and network issues for the user. Opportunistic roaming and national roaming might be implemented in countries to mitigate these challenges for both operators and users.

During the analysis of the model and new user association scheme, some simplifications and assumptions are made which might affect the accuracy of the results. In the simulation, it's assumed that there is an equal distribution of users among MNOs, but this is not the case in real life. Also, while doing the performance analysis of full sharing scenario and operators, we do not consider the different areas such as urban and rural. Furthermore, we only consider the full sharing as our approach and backup was a limitation of this work. Enabling the backup means the user can connect to any BSs when their MNO is unavailable [9]. The effect of backup is a crucial setting to consider because it has several advantages for cellular networks such as enabling it between MNOs improves the network performance and reliability, resulting in better FSP and decreased total power consumption and FDP. These improvements highlight the importance of this backup system in increasing the efficiency and performance of MNOs.

7 CONCLUSION

In this paper, we investigated the potential benefits and challenges of national roaming in terms of power consumption, energy saving, and QoS. We compared two scenarios: full sharing and no cooperation. Simulation results show that in terms of power consumption and the fraction of the satisfied population, full sharing performs significantly better than no cooperation. Implementing full sharing leads to a 27.78% decrease in power consumption and an increase in FSP by 28.67%. These results demonstrate that NR-full sharing enhances energy efficiency, and quality of service and is an effective strategy for reducing the power consumption in cellular networks. Moreover, the proposed user association scheme aimed at focusing on power consumption while maintaining the QoS requirements. The results revealed that adapting the new user association scheme with full sharing leads to more reduction in power consumption with better user satisfaction.

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A APPENDIX

During the preparation of this work, the author used Grammarly and ChatGPT: for help with writing and improving text in order to deliver a professional and coherent sounding text. After the use of these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.