

National roaming as a fallback or default?

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Abstract—Mobile network operators (MNOs) in a country operate independent of each other, although inter-operator collaboration such as national roaming (NR) can offer benefits in terms of resilience, coverage, throughput, and energy efficiency. In some countries, regulations impose realization of national roaming as a fallback strategy, e.g., when an operator cannot offer sufficient coverage while the other can. However, tighter inter-operator collaboration can unlock even more opportunities. In this work, we quantify the benefits in terms of coverage, capacity, and power consumption that can be gained by national roaming as a fallback strategy and as a default strategy wherein all MNOs are operated as a single network. We use public data from national bodies in the Netherlands to study the gains for the Dutch MNOs and investigate the resilience gain also under random failures of base stations, e.g., due to hardware or software errors. Our analysis shows that all MNOs can benefit from a tight cooperation reflected in lower fraction of disconnected population, higher fraction of satisfied population, and lower power consumption for transmission. Despite not offering the same level of benefits, NR as a fallback strategy can also offer gains, in particular for MNOs with less ubiquitous network deployment. Moreover, in comparison to no cooperation, both cooperation approaches provide resilience to isolated failures and result in less severe performance degradation.

I. INTRODUCTION

Ensuring a ubiquitous mobile network coverage and stable connection performance is essential for mobile network operators (MNOs) to sustain their business and for users to have a high service quality. Hence, an MNO has to deploy sufficient infrastructure and typically over-provision it to meet the varying load and requirements of heterogeneous applications in the network. Despite these efforts, still MNOs might suffer from network outages or insufficient performance levels due to some unexpected events such as software or hardware errors. National roaming (NR) or other flavours of cooperation among MNOs can be a quick and financially appealing solution to provide resilience to such disruptions, rather than expanding the infrastructure and over-provisioning the network [1]–[3].

As Fig. 1 depicts, inter-MNO collaboration can help mitigate the coverage holes, increase signal strength perceived by the end users, and save energy. Indeed, prior studies show the benefits of infrastructure sharing in terms of energy consumption [4], [5], resilience to failures [6], and investment and operational costs [7]. In our prior work [6], we investigated the potential coverage and capacity improvements unlocked by cooperation of MNOs in the Netherlands across different geographic regions using the data from the national bodies on

population distribution, cellular network deployments, and urbanity levels. For a hypothetical scenario where all MNOs act as a single national operator and user association is centrally managed considering all users and base stations (BSs), our system level simulations showed that national roaming (NR) can consistently offer up to 13% improvement in *fraction of disconnected population* and up to 55% in *fraction of satisfied population*. Moreover, in agreement with prior studies [8], our study suggests that Dutch MNOs are highly resilient in terms of provided coverage to isolated failures, in which BSs might fail independent of each other. We define resilience in this context as the ability of an MNO to keep its service level not drastically-affected by disruptive events. In a failure scenario, the throughput per user degrades due to the surviving BSs serving more users compared to the pre-failure scenario. In case of correlated failures, where BSs in a certain geography have similar failure likelihood, failures have a more significant impact; more coverage gaps and lower throughput. NR can mitigate this detrimental impact of network failures where failures are isolated in most cases. In case of correlated failures, we see a similar trend when the affected region is small. On the contrary, for failures in a larger area, the benefits of NR diminish, calling for alternative approaches, e.g., aerial connectivity solutions or cells on wheels [9].

While our prior work [6] validates the promise of inter-MNO cooperation to act as a single national MNO (we refer to this scenario as *NR-full* scenario), its realization is challenging as it requires information collection from all MNOs in real-time for optimal association of users to the MNOs. In this paper, we also investigate NR as a fallback strategy (*NR-fallback*) shown in Fig. 1a. Under NR-fallback, a user can connect to the BS of another MNO if its own operator's network cannot provide sufficient signal quality. This strategy has already been implemented in some countries to enable new entrants to the market who cannot cover the whole country in a limited time (in France [10]) or to ensure communications in case of disasters (in the US [9] or in Ukraine [11]) or coverage problems [1], [2]. While coverage holes can be avoided by NR-fallback (Fig. 1a), other benefits illustrated in Fig. 1b and Fig. 1c emerge only if MNOs cooperate more tightly than only cooperating in cases of coverage holes. While there are business aspects that should be considered in realization of NR, e.g., cost settlement or market dynamics, our aim is to quantify the coverage, capacity, power consumption, and resilience implications of different modes of NR.

In this paper, we aim at addressing the following research questions: (i) *How much performance difference can NR-full*

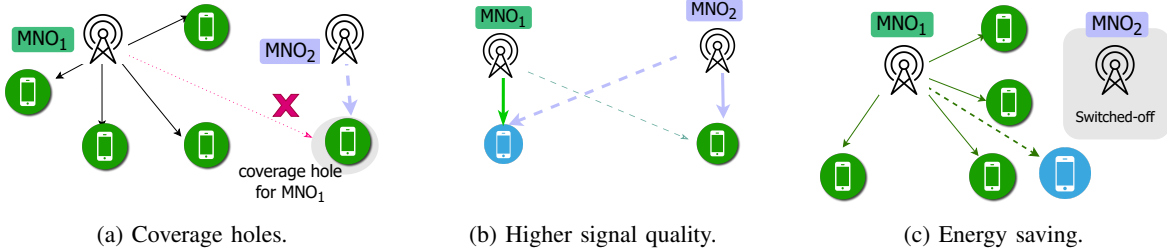


Fig. 1: Infrastructure sharing offers various benefits: (a) avoiding coverage holes of an MNO when the other MNO has a BS in proximity of the user under outage, (b) higher signal quality by letting each user connect to the BS offering the highest signal quality, potentially increasing data rates and decreasing power consumption, and (c) energy savings by steering the users of lightly-loaded BSs to other BSs so that lightly-loaded BSs can go into sleeping state.

maintain over NR-fallback and no cooperation? (ii) How do the benefits vary across MNOs? Is there any performance benefit for the highest-performing MNO to opt for NR options?, and (iii) How much resilience gains can NR schemes provide in case of isolated failures of BSs? To address these questions, first, we show the benefits of NR-full for an MNO with a theoretical analysis using stochastic geometry. Next, using our datasets, we quantify the coverage, capacity, and power consumption performance of NR-full and NR-fallback strategies in comparison to no cooperation setting, for three Dutch municipalities with different sizes. Different from prior studies [4], [5], [7], [12], our paper provides a data-driven analysis considering coverage, throughput, and power consumption performance achieved under two NR schemes. Moreover, our contribution is that we analyze the impact of random failures on the key performance indicators under the considered NR schemes to develop some insights on the resilience facilitated by NR. To the best of our knowledge, no prior work quantifies the benefits of NR-fallback and NR-full at a national scale.

The rest of the paper is organized as follows. Sec. II introduces the considered system and NR schemes. Leveraging stochastic geometry, Sec. III offers some insights on the necessary BS density for infrastructure sharing to be beneficial for an MNO. Next, Sec. IV presents a case study on Dutch MNOs using public data from public bodies to study the gains or losses for each MNO and investigate the resilience gain under random failures of the BSs. Sec. V concludes the paper.

II. SYSTEM MODEL

We consider a setting consisting of N MNOs where MNO $_i$ has K_i BSs to serve its subscribers. Each BS is allocated W_i MHz bandwidth according to the frequency planning applied by MNO $_i$ and is allowed to transmit with a maximum power level of P_{\max} . We denote the transmission power of a BS by P_{tx} where $P_{tx} \in [0, P_{\max}]$. For user association, we assume that BSs broadcast their cell-specific information with the maximum allowed power level P_{\max} . Consequently, each user is connected to the least-loaded BS of its MNO whose signal-to-interference-and-noise-ratio (SINR) is the highest for this user [6]. After users are associated, we assume that the BSs apply a power adaptation scheme to minimize power

consumption while still keeping their users satisfied. Each BS allocates time proportional to the rate requirement over achievable data rate to all of its users [6]. For interference mitigation and power saving purposes, each BS reduces its power to the minimum necessary power that is sufficient to maintain the minimum rate required by its users. Consequently, a BS updates the time allocated to each user. This procedure results in less interference in the network, potentially allowing new connections. Each MNO checks whether the initially-disconnected users can now establish a connection.

The performance of a user can be characterized by two metrics: whether its signal quality is above the minimum signal level SINR_{\min} for establishing a connection with the network (if not, we refer to this user as *disconnected user*) and whether its satisfaction level (which reflects the user's perceived data rate) is sufficient for its application. If a user's data rate is above a minimum required rate (R_{\min}), we refer to this user as a *satisfied user*. The performance of the entire network, either per MNO or with all MNOs together, can then be characterized by the *fraction of disconnected population* (FDP), reflecting the number of users that do not have sufficient signal quality, and the *fraction of satisfied population* (FSP), reflecting the number of satisfied users. FDP and FSP reflect *coverage* and *capacity* of an MNO, respectively. We also report the total power consumption considering the sum of BS powers used for transmission.

Let us consider a user who is subscribed to MNO $_i$ and under coverage of BSs belonging to MNO $_k$, $k \neq i$. For this user, we consider the following three scenarios: (i) *no cooperation* as our baseline reflecting the current operation of MNOs, (ii) *NR-full*: all MNOs operate as a single national MNO as investigated in [6], and (iii) *NR-fallback* where two MNOs in a business agreement can use each other's network if their own network does not have network coverage. For example, in Fig. 1a, MNO $_1$ has a coverage hole whereas MNO $_2$'s signal at the user under outage is above the required minimum signal level. In this case, this user can be associated to MNO $_2$'s network. This scenario is expected to increase the resilience of an MNO to events affecting only one MNO's network, e.g., due to software or hardware failures. In this case, unlike NR-

full scenario, only some MNOs are cooperating. There can be different cooperation options, e.g., an MNO cooperating with n out of all $(N - 1)$ MNOs. We assume that cooperation is bidirectional, e.g., MNO $_i$ and MNO $_k$ both agree to serve each other's users. When there is no coverage hole, the SINR of user i is then $\text{SINR}_{i,j} = \max(\text{SINR}_{i,1}, \dots, \text{SINR}_{i,K_i})$ as in the no cooperation scenario. However, when $\text{SINR}_{i,j} \leq \text{SINR}_{\min}$, then the SINR and resulting data rate depends on the serving BS's signal and bandwidth allocation approach.

III. BENEFITS OF INFRASTRUCTURE SHARING

This section aims at providing some insights on the potential capacity benefit of NR-full offered to an MNO. For the sake of analytical tractability, let us assume that users and BSs of each MNO are distributed following a Poisson Point Process with densities λ_U and λ_{BS} , respectively. We assume a free-space path loss model with exponent $\alpha = 2$ and assume that every user connects to the closest BS. For such a network without any cooperation with other networks, expected theoretical capacity perceived by a user can be calculated according to the Shannon's capacity formula as:

$$\mathbb{E}(C) = \frac{W}{D_{BS}} \log_2(1 + \text{SNR}), \quad (1)$$

where W is the total bandwidth available at a BS, D_{BS} the number of users connected to this BS and SNR the signal-to-noise ratio. Leveraging stochastic geometry, we derive analytically in [13] the expected user capacity $\mathbb{E}(C)$ when the BS density is small enough, i.e., $\lambda_{BS} < \frac{1}{\pi}$:

$$\mathbb{E}(C) = \frac{W\lambda_{BS}}{\ln(2)\lambda_U} \left(\ln \left(\frac{\lambda_{BS}\pi P_{tx}}{N_{\text{tot}}} \right) + \gamma - \lambda_{BS}\pi \right) + \delta_1, \quad (2)$$

where N_{tot} is the total noise power of the link, γ is Euler's constant, and δ_1 is the approximation error (Theorem 1, [13]). Similarly, we derive the expected capacity for NR-full scenario according to (2) with increased BS and user densities.

Let $\lambda_{BS}^{(i)}$ and $\lambda_U^{(i)}$ denote the BS and user density of MNO $_i$, respectively. Consequently, we can define $\lambda_{BS} := \lambda_{BS}^{(1)}$ and denote the BS and user density in the NR-full scenario by $\lambda_{BS}^{nr} := f_{BS}\lambda_{BS}$ and $\lambda_U^{nr} := f_U\lambda_U$ for $f_{BS}, f_U > 1$, where f_{BS} and f_U are defined as follows:

$$f_{BS} := \sum_{i=1}^N \frac{\lambda_{BS}^{(i)}}{\lambda_{BS}} \quad \text{and} \quad f_U := \sum_{i=1}^N \frac{\lambda_U^{(i)}}{\lambda_U}. \quad (3)$$

We can then calculate the capacity difference $\Delta\mathbb{E}(C)$ between no-cooperation and NR-full scenarios as follows:

$$\begin{aligned} \Delta\mathbb{E}(C) &= \frac{W\lambda_{BS}}{\ln(2)\lambda_U} \left(\ln \left(\lambda_{BS}\pi \frac{P_{tx}}{N_{\text{tot}}} \right) + \gamma - \lambda_{BS}\pi \right) \\ &\quad - \frac{Wf_{BS}\lambda_{BS}}{\ln(2)f_U\lambda_U} \left(\ln \left(f_{BS}\lambda_{BS}\pi \frac{P_{tx}}{N_{\text{tot}}} \right) + \gamma - f_{BS}\lambda_{BS}\pi \right) \\ &= \frac{W\lambda_{BS}}{\ln(2)f_U\lambda_U} \left((f_U - f_{BS})\gamma + (f_{BS}^2 - f_U)\lambda_{BS}\pi \right) \\ &\quad + (f_U - f_{BS}) \ln \left(\lambda_{BS}\pi \frac{P_{tx}}{N_{\text{tot}}} \right) - f_{BS} \ln(f_{BS}) \end{aligned}$$

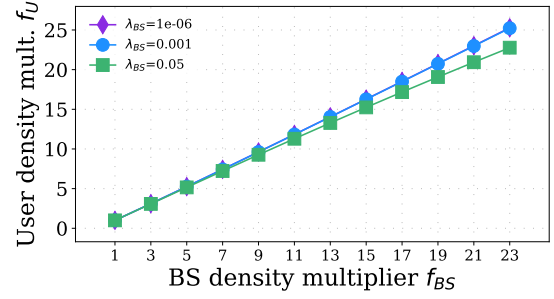


Fig. 2: All values below the lines show regimes of f_{BS} and f_U in which it is beneficial to share the network for $P_{tx} = 30$ dBm, $N_{\text{tot}} = -65.9$ dBm.

$$\begin{aligned} &= \frac{W\lambda_{BS}}{\ln(2)f_U\lambda_U} \left((f_U - f_{BS})\gamma + (f_{BS}^2 - f_U)\lambda_{BS}\pi \right) \\ &\quad + (f_U - f_{BS}) \ln \left(\pi \frac{P_{tx}}{N_{\text{tot}}} \right) \\ &\quad + (f_U - f_{BS}) \left(1 + \lambda_{BS} + O \left(\frac{1}{\lambda_{BS}^2} \right) \right) - f_{BS} \ln(f_{BS}), \end{aligned}$$

using the first-order Taylor expansion $\ln(x) = 1 + x + O(\frac{1}{x^2})$ for $|x| < 1$. To investigate when NR-full leads to higher average user capacity, we derive the value of λ_{BS} for which the term in brackets becomes negative, thus resulting in $\Delta\mathbb{E}(C) < 0$.¹ The critical BS density is then:

$$\begin{aligned} &(f_U - f_{BS})\gamma + (f_{BS}^2 - f_U)\lambda_{BS}\pi + (f_U - f_{BS}) \ln \left(\pi \frac{P_{tx}}{N_{\text{tot}}} \right) \\ &\quad + (f_U - f_{BS}) (1 + \lambda_{BS}) - f_{BS} \ln(f_{BS}) < 0, \\ &\lambda_{BS} < \frac{f_{BS} \ln(f_{BS}) + (f_{BS} - f_U) \left(1 + \gamma + \ln \left(\frac{\pi P_{tx}}{N_{\text{tot}}} \right) \right)}{f_{BS}(f_{BS}\pi - 1) + f_U(1 - \pi)}. \end{aligned}$$

Fig. 2 shows the maximum values for f_{BS} and f_U under different BS densities, where all settings below the line will result in higher capacity under NR-full. When $f_{BS} = f_U = f$, we can derive the required BS density λ_{BS} where NR-full leads to lower capacity: $\lambda_{BS} < \frac{1}{\pi} \frac{\ln(f)}{f-1}$. For Dutch cellular networks with three MNOs, this means that sharing is always beneficial as the BS density varies from $1 \cdot 10^{-7}$ to $1 \cdot 10^{-5}$ BSs per m². We refer the reader to [14] for more details about the benefits of NR-full with different BS and user densities.

In the NR-fallback scenario, users connect to their own network, unless they are under outage. In the model described above, we calculate the capacity for every user without paying attention to whether their SNR is sufficient to decode the received signal (e.g., encoded with the most robust modulation scheme). If we consider the cases wherein the user's signal level is lower than SNR_{\min} , the number of users connected to a BS (D_{BS}) decreases in (1), while SNR increases. We define the fraction of users that are under outage as follows:

$$p := \mathbb{P}(\text{SNR} < \text{SNR}_{\min}) = \exp \left(-\frac{\lambda_{BS}\pi \frac{P_{tx}}{N_{\text{tot}}}}{\text{SNR}_{\min}} \right). \quad \text{If we assume}$$

¹We omit the first term as W , λ_U , and λ_{BS} are non-negative and the approximation error is typically negligible.

equal densities and coverage probabilities for all MNOs, this means that a fraction p of their users tries to re-connect to another operator. Therefore, for a given operator, the fraction of users that uses another network and the fraction of users from other operators that use this network cancels out.

While quantifying the increase in SNR is challenging, we reason that in the NR-fallback scenario the expected channel capacity per user increases compared to no cooperation, assuming an identical BS and user densities across all operators. When the densities are different, this could mean that the number of users served by a BS increases for MNOs with higher BS density, which then decreases the expected channel capacity per user for that MNO. In the following section, we investigate the performance of each MNO using the real data from the Netherlands to provide insights on these dynamics.

IV. A CASE STUDY ON DUTCH CELLULAR NETWORKS

We perform a case study on the Dutch MNOs, based on available data about cell towers, population distribution, and urbanity levels. In the following, we first provide an overview of the datasets [6] and simulation parameters, before presenting the performance of the considered schemes.

Overview of the datasets: We use two datasets: the Dutch Telecommunication Authority’s antenna registration dataset [15] and the population data per $500\text{m} \times 500\text{m}$ square from Statistics Netherlands [16]. The cellular network dataset provides the location, technology (3G, 4G, 5G), center frequency, effective radiated power, height, and sectors per registered BS in the Netherlands. We refer to the three MNOs operating in the Netherlands as MNO₁, MNO₂, and MNO₃. The number of BSs varies from around 8000 (MNO₃) to 13000 (MNO₂) at the time of conducting this study. The population dataset provides information about the population and the urbanity level per $500\text{m} \times 500\text{m}$ square. We use urbanity levels to map the type of BS-user link to the two channel models used in 3GPP TR 38.901 specification [17], namely an urban macrocell (UMa) or a rural macrocell (RMa). For example, an area with lower than 500 per km^2 address density, the urbanity level is identified as 5 and the corresponding channel model is RMa as this is a sparsely populated region.

Simulation settings and scenarios: Most of the BSs have a three-sector antenna. Hence, we adopt the 3GPP antenna gain model for these three-sector antennas [18]. For the user equipments, we assume omnidirectional antennas, i.e., 0 dB receiver antenna gain. Considering the urbanity level of the area and corresponding channel model in [17], we calculate the received signal strength and consequently SINR at a user. We assume that only a fraction of the population in each area is active at a time, e.g., 2% while the rest is connected via Wi-Fi or not in active communication. Since the public data on the distribution of customers among the MNOs is inconsistent, we assume that all MNOs have an equal number of users. Users’ rate requirements are driven randomly between 8 and 20 Mbps where 8 Mbps is the minimum outdoor data rate to be provided by an MNO according to the regulations asserted by the Dutch regulatory body RDI [19]. We performed simulations to

calculate the FDP, FSP, and power consumption for the considered settings for three municipalities with different size and populations, namely Amsterdam, Enschede, and Middelburg.

We consider two NR-fallback scenarios: (1) all MNOs work together, and (2) MNO₂ and MNO₃ are in a business agreement, hence MNO₁ operates without any collaboration (*NR-fallback 2&3* in the figures). We select this later setting as our prior study [6] reveals that MNO₃ consistently has higher FDP and lower FSP while MNO₂ outperforms others. Therefore, this setting reflects a scenario where it might be beneficial for MNO₃ to use MNO₂’s network but vice versa might not help users of MNO₂. For NR-fallback scenario, users are first associated to one of the BSs of their own MNO. Then, after all users with $\text{SINR} \geq \text{SINR}_{\text{min}}$ are connected to a BS of their own MNO, users in coverage holes are connected (in random order) to a BS of one of the other MNOs.

Results: First, we assess the performance without any failures in the network. As the observed trends are similar for the considered cities, we report only the results for Amsterdam. Fig. 3a shows that considering the whole population of customers, NR-full results in the highest FSP improvement over no cooperation (~ 0.18) while the benefit experienced by each MNO might differ depending on their infrastructure, e.g., MNO₃ benefiting more compared to MNO₂. Comparing NR-full with NR-fallback schemes, the FSP difference varies from 0.10 to 0.15. When only MNO₂ and MNO₃ collaborate, the FSP is slightly lower compared to when all three MNOs implement NR-fallback. While NR-fallback maintains a higher FSP compared to no cooperation for MNO₁ and MNO₃, this is at the expense of a slight degradation in FSP of MNO₂. When it comes to FDP performance, Fig. 3b shows that NR-fallback and NR-full achieve almost zero disconnected population. Moreover, NR-fallback and NR-full scenarios have equal FDP, since users that cannot connect to a BS from any MNO can certainly not connect to a BS from their own MNO. Fig. 3c shows that NR-full leads to the lowest power consumption ($\sim 3 \times$ lower in comparison to no cooperation) by facilitating users getting service from the closest BSs, hence requiring lower transmission power. However, the NR-fallback schemes consume more power ($\sim 10\%$) than the no-cooperation scenario. This is due to the users under outage at their own MNOs, but that are served by national roaming by other MNOs, corresponding to around 2% as seen in Fig. 3b.

Fig. 4 shows which users are served by which MNOs under NR-fallback and NR-full for Amsterdam with around 1700 BSs in total. Note that we assume an equal number of customers per MNO. Hence, each MNO is expected to serve 100% of the users if FDP is zero and there is no cooperation. In NR-fallback (left figure in Fig. 4), around 20% of the users are roamed to other MNOs. For instance, 9.79% of MNO₃’s customers are now served by MNO₂ while 2.15% of MNO₂’s customers are served by MNO₁. In the NR-fallback scenario, around 15% of the users that are subscribed to MNO₃ connect to BSs of MNO₁ or MNO₂. However, since the coverage of MNO₁ and MNO₂ is already high compared to MNO₃, only a small fraction of users is roamed to MNO₃: around

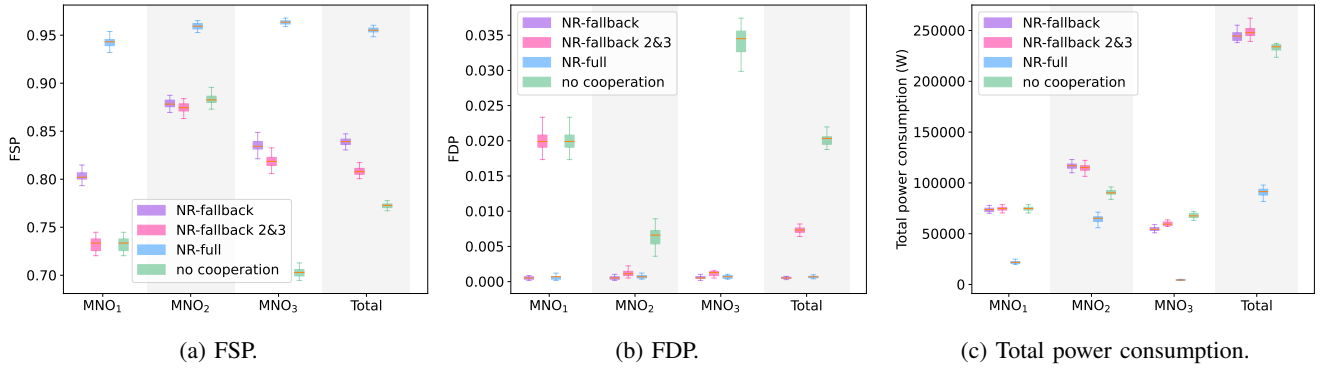


Fig. 3: FSP, FDP, and total power consumption of each MNO for Amsterdam.

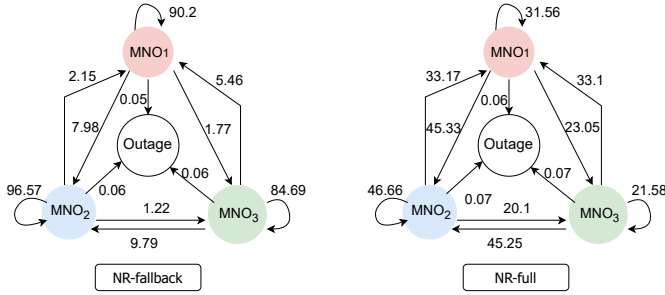


Fig. 4: Percentage of customers in Amsterdam being served by each MNO. An arrow shows the percentage of customers of an MNO being roamed to another MNO.

3%. Therefore, MNO₃ benefits more from the NR-fallback scenario in terms of FDP and FSP, while MNO₁ and MNO₂ only have less resources to divide among their own users, which results in slightly lower FSP for MNO₂ compared to no cooperation (Fig. 3a). When it comes to NR-full, we observe a very different distribution: MNO₂ serves $\frac{137.24}{300}$ fraction of the customers while MNO₁ and MNO₃ serve $\frac{97.83}{300}$ and $\frac{64.73}{300}$ fractions, respectively. While MNO₂ now serves many more customers (more than 100%), it only serves 46.66% of its own customers and the rest is roamed to other MNOs due to the association scheme that favours the closest BSs independent of the ownership of that BS. Due to this trend, we observe a significantly lower power consumption in Fig. 3c maintained by NR-full in comparison to NR-fallback scheme. Note that MNOs that have a dense deployment can financially benefit from these operation modes via cost settlement among MNOs, e.g., based on the number of served customers.

Failures: MNOs might suffer from BS failures due to various reasons, from power outages to human errors or hardware failures [1]. To investigate the benefits NR approaches can offer in such cases, we simulate *isolated failures*, where 10% of the randomly-chosen BSs fail. We report the performance after BSs fail and users connect to the surviving BSs. To investigate the trends for different cities, Fig. 5 depicts the performance change after failures in comparison to the performance maintained prior to the failure: values in the red

shaded region stands for the performance decline while values in the unshaded region represent improvement. Moreover, the lower difference implies higher resilience. Fig. 5a shows that both NR-fallback and NR-full provide resilience against such failures and ensure that the FDP remains intact, i.e., $\Delta\text{FDP} \approx 0$. Interestingly, we observe $\Delta\text{FDP} < 0$ when the MNOs operate independently. We attribute this trend to the decreasing interference after failures of some BSs. Consequently, a small fraction of the population can now establish a connection. For instance, the FDP decline in Amsterdam is around 0.005 for MNO₁ and 0.003 when considering all MNOs. In smaller cities like Enschede and Middelburg, we can argue that MNOs are resilient to failures as they have already a sufficiently-dense deployment and isolated failures lead to either marginal or no change in FDP even without any inter-MNO cooperation.

Fig. 5b shows that, for bigger cities like Amsterdam and Enschede, isolated failures might lead to a lower satisfaction ($\Delta\text{FSP} < 0$). However, NR-full decreases this detrimental impact to around 0.02. Considering the total population and all MNOs performance together, NR-fallback and no cooperation lead to almost the same FSP decline. However, for different MNOs, we observe different trends; MNO₂ maintains a lower FSP decline for its own customers if it does not opt for cooperation; and MNO₃ benefits the most in terms of FSP increase. This is in line with our earlier observation that MNO with a more dense deployment might not benefit from NR-fallback scheme. Finally, Fig. 5c depicts the difference between the average total power after failures and before the failures, divided by the power consumption of no cooperation before the failures. Fig. 5c shows that after failures the MNOs need to consume more transmission power to serve the users that were served by those failing BSs in the pre-failure scenario. For NR-full, however, this necessary additional power is markedly lower compared to other schemes.

To summarize, NR approaches provide a significant improvement in FDP and FSP, hence facilitating a more resilient network. The highest performance gains are achieved by NR-full. However, NR-fallback schemes can also provide benefits in comparison to the baseline where MNOs operate separately. The benefits, however, are disproportionate; MNOs with less dense BS deployment benefit more while MNOs with dense

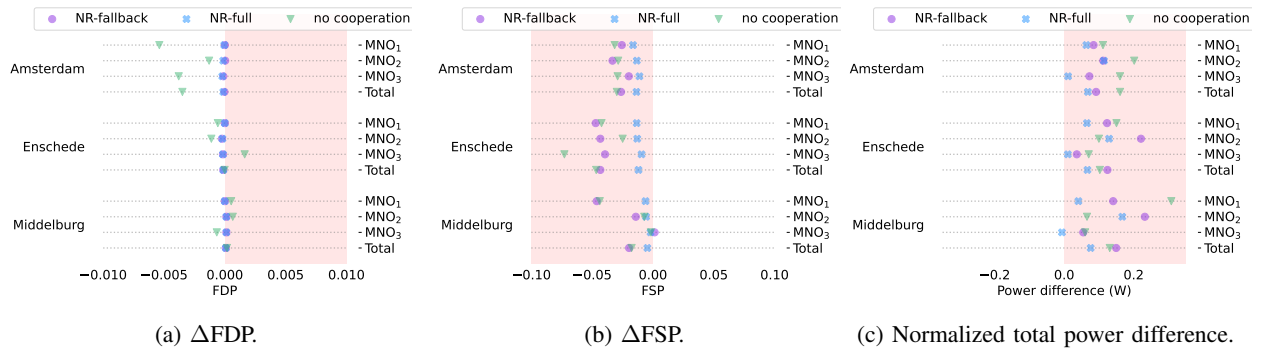


Fig. 5: Difference in the average of FDP, FSP, and total power consumption after isolated failures.

deployments might experience performance degradation (in the studied settings, marginal only) as previously disconnected users are served by these MNOs with ubiquitous deployments. More advanced roaming approaches, e.g., prioritizing the MNO's own users, can mitigate such effects. As for the impact of failures, all MNOs are already resilient to isolated failures as they have sufficiently dense BS deployments which can instantaneously cover the users of the failed BSs. However, NR schemes are still beneficial as they can alleviate the throughput decrease by offering service from BSs of other MNOs.

V. CONCLUSIONS

In this paper, we investigated benefits offered by national roaming in terms of coverage, capacity, and power consumption. We compared two schemes (i) NR-fallback: national roaming strategy activated only when an operator cannot offer coverage but other operator(s) can, and (ii) NR-full: all operators are operated as a single network. Our simulation results using data from the Netherlands show that the NR-full outperforms the NR-fallback significantly in all performance metrics, namely fraction of satisfied population, fraction of disconnected population, and power consumption. When comparing NR-fallback with no cooperation, we also observe performance benefits for some operators and considering the whole population. In case of random failures of base stations, due to the dense deployment of the base stations, networks are resilient in terms of providing sufficient coverage. However, NR schemes offer more resilience reflected as less severe throughput decline and power consumption increase. Possible future directions include business implications (market stability), cost settlement among the operators to make such collaborative operation appealing to the operators, and analysis on the implementation complexity, which play a key role in decisions of the operators and the regulatory bodies.

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