Saving Energy in Cellular Networks through Resource Sharing

LYNN VAN DER HORST, University of Twente, The Netherlands

Fig. 1. Transmitters on a base station

As mobile networks grow in both user numbers and throughput, so does their energy consumption. Upward trends in energy prices are a strong motivator for network operators to set up a more efficient system. Besides direct monetary costs, there are other motivators such as climate impact and network resilience. One possible solution to these problems is for network operators to share their resources. In this paper we will investigate to what extent cellular networks can save energy through resource sharing.

Additional Key Words and Phrases: Cellular Network, Resource Sharing, Energy, Simulation

1 INTRODUCTION

The telecom industry currently consumes about 2-3% of all energy generated globally. A transition to higher frequencies in combination with a significant rise in traffic will likely multiply the current energy consumption by a factor of 2 to 3 [13]. Many national governments are already pressuring the telecom sector to work towards a greener carbon footprint, and stronger limitations on emissions are expected in the future. Besides external motivators, energy consumption also makes up a large portion (20-40%) of the operational expenditure of cellular networks [13].

There are many approaches that can contribute to the efficiency of cellular networks. Such strategies include traffic offloading, base station sleep modes and reductions to the number of manufactured base stations, among others [9][16][28]. Although developments in the technology of cellular networks are certainly promising, one opportunity is easily overlooked: multiple mobile network providers are often active in the same area. In the Netherlands, cellular network connections are divided over three major operators: KPN, T-Mobile, and VodafoneZiggo [5]. In general, these providers cooperate only to a very limited extent [6].

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1.1 Research Questions

The main research question this paper will attempt to answer is: *To what extent can resource sharing improve the energy efficiency of the Dutch cellular network?* It will attempt to do so by using several sub-research questions. These are listed below:

- **Q1:** *What possible ways are there to do resource sharing in cellular networks?*
- **Q2:** *To what extent is resource sharing currently implemented in the Dutch cellular network, and what limitations can be found?*
- **Q3:** *How much energy can be saved in the Netherlands if different levels of resource sharing are implemented in the cellular network?*

The purpose of this paper is to investigate what reductions resource sharing alone can make to the energy consumption of the Dutch cellular network. The conclusions made in this paper could help network operators and policymakers when making decisions about the future of the Dutch cellular network, and by extension, other, similar mobile networks.

In section 2, we will consider other works related to this research. In this section, we will also attempt to answer RQ1 and RQ2, as these questions can be answered through literature research alone. In section 3, we will go over the design and models we used to construct a simulator of the Dutch cellular network. In section 4 the results gathered from the simulator will be explained. We draw our conclusions in section 5. Finally we will discuss a number of flaws and abstractions that may impacted our results in section 6.

2 RELATED WORKS

There have been numerous publications on the topic of resource sharing in cellular networks. These publications discuss various aspects of resource sharing. An article by GSMA offers an overview of the current problems, technologies and costs of infrastructure sharing [14]. Such generalized specifications are very useful for smaller scale research.

Another paper directly investigates the advantages of infrastructure sharing, specifically in 5G networks [12]. The paper not only focuses on maintaining QoS (Quality of Service), but also on energy efficiency. The paper compares various different configurations for 5G base stations by experimentally determining their performance. Due to its focus on energy efficiency, this paper is highly related to our main research question.

There are also papers that focus on resource sharing for managing data throughput, rather than just for energy efficiency. One such papers compared different strategies for resource sharing through simulation [26]. Nearly all related works conclude that there are benefits to resource sharing, at least from an external perspective.

Most papers on resource sharing in cellular networks do not even mention energy efficiency. The ones that do usually consider it a secondary objective, citing theoretical gains at best. This paper instead will focus on directly estimating the levels of energy that resource sharing can save in a large scale cellular network. We hope to provide a tangible value that shows what exactly these benefits could be.

2.1 Methods of Resource Sharing

We define mobile network resources as the hardware, software and legal allowances that an MNO (Mobile Network Operator) has. MNOs can share these resources to various extents, and through various schemes. We will consider three groups of prevalent strategies: *Passive Sharing, Active Sharing, and Roaming Based Sharing*

2.1.1 Passive Sharing. Passive Sharing involves an MNO sharing the passive structures of their base stations with another MNO. This mainly includes towers and sites. This form of sharing has little effect on the network itself, but it can provide cost and environmental benefits [8][18].

2.1.2 Active Sharing. Active Sharing involves MNOs sharing the active components of the mobile network between multiple operators. This includes antennas, backhaul equipment, network switches, and frequency bands [8][18].

In order to allow multiple operators to exist within the same region, the total available radio spectrum is usually divided between them [3]. Because operators can only use their own frequency bands, the situation allows for scenarios where some operators run out of resources while others have resources to spare. Spectrum Sharing is a way to alleviate this inefficiency.

Spectrum sharing is a form of Active Sharing where MNO-1 can lend a part of its frequency band to MNO-2 (and vice versa) [3]. It can be implemented in many ways. One method is that MNO-1 can 'lend' a partition of its spectrum to MNO-2 if MNO-2 has a higher demand. Spectrum Sharing can thus also be used as a form of 'last resort' sharing [21][26]. Another method involves MNO-1 permanently sharing a fraction of its frequency band with MNO-2, using a time slot system to determine which MNO gets which channel at any moment [17].

Active Sharing is usually considered from the perspective of QoS, and not necessarily that of energy efficiency [17][21][26].

2.1.3 Roaming Based Sharing. We define roaming based sharing as a form of resource sharing where UEs (User Equipments) of MNO-1 can access the network of MNO-2 under certain circumstances (and vice versa).

We can model Roaming Based Sharing as a form of 'last resort' sharing. In the scenario that MNO-1 has a sector with high demand, it can transfer a number of UEs to a sector of MNO-2 that has supply to spare. This serves to prevent overload scenarios, in which a base station is unable to serve its UEs because the demand for it is too high[26]. Network sharing only occurs if the alternative is to provide no service at all. Simulations show the effectiveness of this strategy especially for QoS [15].
In such an implementation of Roaming Based Sharing, MNOs can retain their own physical infrastructure and frequency bands, and are required to collaborate on a more abstract level. The only requirement is that MNO-2 is able to service UEs from MNO-1 if needed (and vice versa).

In the studies we investigated, Roaming Based Sharing was never implemented with the intention of improving energy efficiency. The focus was mostly on coverage and QoS [15][26].

2.1.4 Full Resource Sharing. Because we want to investigate how much energy the cellular network can save as a whole, we will define a fourth strategy that employs resource sharing to a greater extent. We will call this strategy Full Resource Sharing (FRS). In order to achieve it, UE's must be able to connect to any base station, regardless of MNO. The idea of an MNO thus becomes irrelevant to the structure of the network itself.

2.2 Resource Sharing in the Netherlands, and its Limitations

Thus far, we can conclude that resource sharing in cellular networks can be conducted to many degrees. A report from the Netherlands Authority for Consumers and Markets, (ACM) from 2021 discusses the state of resource sharing in the Dutch mobile network, as well as a perspective into the near future.

Although Dutch MNOs are beginning to work on Passive Sharing, Active Sharing is not (yet) deemed necessary. Although the report does not dismiss Active Sharing entirely, it states that a new independent investigation must first be conducted with regards to changes in competitive relationships. In contrast, several other European countries, including the Czech Republic, Belgium and Italy, have produced agreements on Active Sharing of mobile networking resources [5].

To understand why Dutch legislation seem reluctant in promoting resource sharing, we must consider the reasoning of the ACM. The ACM is an institution under the jurisdiction of the Dutch Ministry of Economic Affairs and Climate Policy [23]. Its responsibility is primarily to protect consumers [7]. It does this by enforcing section 24 of the Dutch Competition Act, which exists to prevent abuse of economic power [22]. If more cooperation exists between MNOs, it is possible for them to artificially raise prices. The decision made by the ACM is meant to protect competition in the Dutch market.

Virtually all limitations on resource sharing in the Dutch cellular network are of legal nature. While passive sharing is seeing usage, currently no large scale Active Sharing or (Consumer) National Roaming can be implemented in the Netherlands. There are, however, a few notable exceptions. Since 2012, the three main MNOs of the Netherlands have an agreement to serve each other's UEs in case of an outage [11]. And one MNO offers Virtual National Roaming as an 'Emergency Service', for organisations that depend strongly on permanent connectivity [29].

3 MODEL DESCRIPTION

The answer to Q3, will rely on simulation results. We will perform four steps in order to simulate the Dutch cellular network.

1. First we need to simulate the network itself. Data sourced from the Dutch government through the 'Rijksinspectatie Digitale Infrastructuur' [27] provides detailed information on bandwidths, MNOs, locations, antenna alignments and type of technology used. We filter this data based on technology type, such that only LTE and 5G base stations remain. The reason for this is that older technologies such as 2G and 3G are actively being dismantled in the Netherlands [2].

2. The second step is to generate the User Equipments, or UEs. Data on population density, which will obviously correlate with the UE density of the cellular networks, is sourced from the 'Nationaal Georegister' [24]. The database used provides population values per zip code, which we assume to be fine grained enough for our application.

We set a percentage of UEs to be active, and we give them a random location within their zip code area. We also give each user a data rate R_{req} which is a random value, uniformly distributed between 8 and 20 Megabits per second. Here, 8 megabits per second is the data rate that should at minimum be available in the Netherlands [19]. The upper bound of 20 megabits per seconds was chosen quite arbitrarily; we will be experimenting with many variations in the number of UEs, the simulator should provide reasonable data for different levels of network saturation.

3. In order to connect our simulated UEs to our simulated Base Stations, we use a model that is strongly based on the model used in [30]. This model was devised with resilience metrics in mind, and not power efficiency. In order to lower the computational complexity of the simulation, we will ignore interference.

We use a similar path loss model as the one in [30]. This model uses an independent probability for path loss for each link in the system. The model itself is based on the 3GPP specification for path loss [1].

We select the 30 channels that have the best Signal to Noise Ratio for each UE, and we check for each of them if they have available bandwidth and transmitter power.

In order to optimize the system further, we keep an array of all BSs, ordered based on the number of UEs each BS can provide coverage to. When selecting a channel (from the selected 30), we always prefer one that belongs to a BS that is higher in this array. This way the number of base stations with 0 UEs is maximized. This is important because such base stations can be set to sleep, which greatly reduces their power draw [4].

4. It now remains to calculate the power usage of the network in multiple scenarios. We will use the (simplified) model proposed in [10] to estimate the power usage of each base station. Although this model was originally meant for LTE base stations, it is cited as applicable to 5G as well [20]. The main formula to find the power of a base station is then Equation 1.

$$p_{bs} = p_{const} + p_{load} + p_{amp} \tag{1}$$

where

$$p_{const} = (n_{sector} \cdot p_{rect}) + p_{link} + p_{airco}$$
$$p_{load} = n_{sector} \cdot (p_{trans} + p_{proc})$$
$$p_{amp} = \frac{P_{out}}{\eta}$$

where n_{sector} the number of BS sectors, p_{rect} the electrical power of the rectifier, p_{link} the electrical power of the microwave link (assumed present), p_{airco} the electrical power of the air conditioning unit, p_{trans} the electrical power of the transceiver, p_{proc} the electrical power of the digital signal processor, P_{out} the total output antenna power, and η the efficiency of the Power Amplifier unit.

The values for all these parameters are constants taken from [10] and [4], except for n_{sector} and P_{out}, which come from the simulator. It should be noted that in this equation, P_{out} is the sum of all p_{out} values for one base station, where each UE link results in one p_{out} value through Equation 3. The constants are denoted in Figure 2.

p_{rect}	100W
p_{proc}	100W
p_{trans}	100W
p_{link}	80W
p_{airco}	225W
p_{sleep}	75W
η	12.8%

Fig. 2. Constants used

It should be noted that n_{sector} refers to the number of antenna arrays present in the base station [20]. In macro base stations, this number is often 3, but not always. We assume that each antenna array has its own TRX chain, which means it has its own power amplifier, transceiver and signal processor.

In case the base station has no UEs, we assume it is automatically set to sleep mode. This still draws some power; we will use the equation proposed in [4], denoted in Equation 2, to calculate this value.

$$p_{bs} = n_{sector} \cdot p_{sleep} \tag{2}$$

The simulator then, should produce the p_{out} value for each UE link. We will get this value by applying Equation 3, which is based on the Friis transmission equation.

$$p_{out} = p_{rec} - G_t + L_p \tag{3}$$

where p_{rec} represents the received power, G_t the gain of the transmitting antenna and L_p the path loss. We can ignore the gain of the receiving antenna if we assume the UE to have an omni-directional antenna [30].

The path loss and the transmitter antenna gain are already calculated in step 3. This leaves us to find p_{rec}, or the power that needs to be received by the UE. We find this value by applying the Shannon-Hartley theorem as denoted in Equation 4

$$p_{rec} = N \cdot (2^{R_{req}/B_{alloc}} - 1) \tag{4}$$

where N represents the noise value, R_{req} the capacity (or UEs bit rate in this case), and B_{alloc} the UE allocated bandwidth.

As suggested in [30], the required UE bandwidth is calculated through another application of the Shannon-Hartley theorem, as denoted in Equation 5.

$$B_{req} = \frac{R_{req}}{\log_2(1 + \frac{S}{N})} \tag{5}$$

where $\log_2(1 + \frac{S}{N})$ is the Spectral Efficiency of the UE, dependent on the Signal-Noise-Ratio with the maximum channel power, found in step 3.

If the channel has bandwidth to spare, the allocated bandwidth B_{alloc} is equal to B_{req}. Otherwise, we use Equation 6 to divide the available bandwidth according to the needs of all UEs.

$$B_{alloc}(U_i) = \frac{B_{req}(U_i) \cdot C_{bw}}{\sum_{j=0}^{K_u - 1} B_{req}(U_j)} \tag{6}$$

where $B_{alloc}(U_i)$ represents the allocated bandwidth for a UE i, $B_{req}(U_i)$ the required bandwidth for a UE i, C_{bw} the total channel bandwidth, K_u the total number of UEs in the channel, and $B_{req}(U_j)$ the required bandwidth for UE n.

In our model we only consider BSs to have a downlink. We leave the power consumption of the UEs out of our calculations as well, and we assume each BS has a microwave link present. We also take complete freedom in assigning resources to UEs. In a real system, there might be more constraints to e.g. the size of the bandwidth blocks that are allocated.

NVIDIA CUDA. Because the model needs to perform many independent, yet complex, calculations per user, a single-threaded implementation is bound to be inefficient. We elected to build our model with NVIDIA CUDA [25]. This API allows for parallel computing on GPU cores called 'CUDA cores'. The availability of many cores allows for a much faster execution of the simulator compared to a traditional approach.

4 RESULTS

4.1 Saving Energy in the Dutch Cellular Network

As discussed in the previous sub-section, we will consider FRS as a theoretical strategy in resource sharing. We will compare this strategy to the one currently in place, and consider the differences in especially power consumption.

We should note that our simulations showed that FRS always results in a greater coverage than No Resource Sharing (NRS). This simply means that there are more unreachable UEs in NRS. This is logical, since an isolated UE has a better chance of finding an available cell tower in FRS. This does affect the resulting power values, however. This is because fewer base stations can go into sleep mode when more UEs are connected; the FRS network is simply servicing a higher percentage of the active UEs.

The availability of the network is beyond the scope of this paper, we only care for the power efficiency. To nullify the coverage difference caused by the greater coverage of FRS, we manually disable a number of UEs to even out the rates of 'UE dissatisfaction' between the two configurations.

For the percentage of active UEs, we consider a range of 0% to 1.75% of the Dutch population.

First we will look at the difference in total wattage. If we consider Figure 3, which displays the total wattage of NRS and FRS for different partitions of the population active, we can see that FRS results in a lower wattage at all times during this interval. It should be noted that the simulator proposed in [30] uses a percentage of 0.5% to represent the active population. This means our interval might extend quite a bit above a 'normal' level of usage. We do this to see what effects occur at higher network occupancies.

We can see that at low network occupancy, the wattage grows quickly for both NRS and FRS. We theorize this is caused by the fact that relatively more BSs need to be active per UE. E.g. in a scenario with only one UE, we have to have one active BS. If we add one extra UE, the probability that it is within the range of that same BS is rather small, and therefore we need to activate one more BS, resulting in a rate of one BS per UE. At a higher occupancy, the probability of a UE being in the range of an already activated BS rises, and therefore the rate of activated BSs per UE is lower, which in turn means the wattage delta is smaller per UE. As the network becomes more populated with UEs and active BSs, the probability that no activated BS is in range shrinks.

We can also see that the graphs are likely going to coincide when about 1.85% of the total population would be active. We can see why this happens when we consider Figure 7, which shows the amplifier power for NRS and FRS when different partitions of the population are active. As the active population grows, the amplifier power of FRS grows much faster than that of NRS. This has to do with the algorithm we use to maximize sleep states. Because FRS has more sleeping BSs, the network has to transmit the same data over a smaller total bandwidth. Through Equation 4, this means P_{rec} has to go up, and this directly influences P_{amp}.

This is an intentional effect: we want to maximize the number of sleeping BSs, not necessarily P_{amp}. We theorize this will have a larger effect on overall wattage reduction. We can see that this is at least true for lower network occupancy's. At around 0.25%, the effect seems maximal. It is clear that at higher loads, perhaps more BSs should be activated in order to ensure that FRS performs better than NRS. It should be noted once again that the assumed 'normal' active percentage of the population is 0.5%.

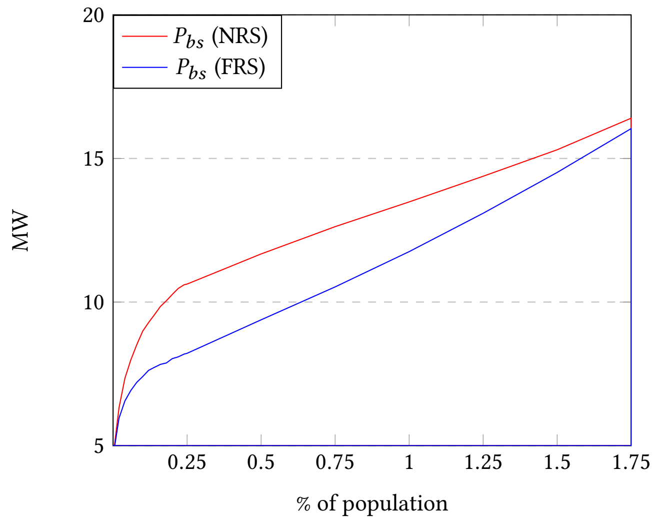

Fig. 3. Total wattage for NRS and FRS

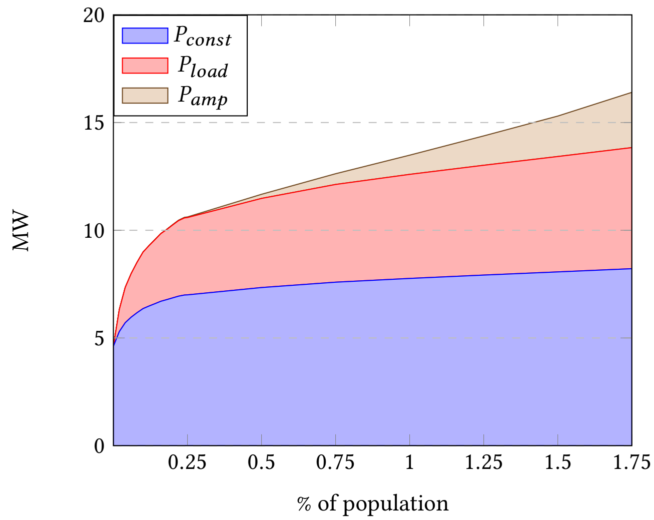

Fig. 4. Division of total wattage for different scenarios in NRS (P_{load} excludes P_{amp} for this graph)

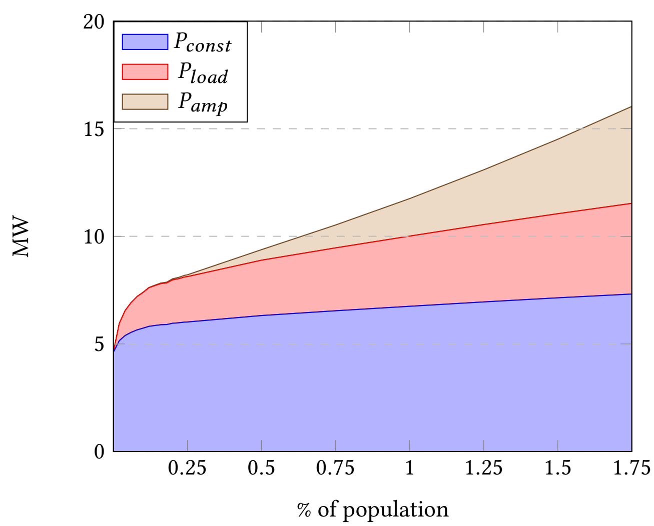

Fig. 5. Division of total wattage for different scenarios in FRS (Pload excludes Pamp)

If we consider Figure 4 and Figure 5, which show what the total wattage is made up from when different partitions of the population are active, we can see how much of the total wattage is made up by P_{amp} for both NRS and FRS. Clearly the increased number of active BSs is helping the performance of NRS in the higher activity levels. In the lower levels, we can see how FRS has a strongly reduced total wattage due to its far lower P_{load} and P_{const}, which are both directly related to the number of active BSs.

The effect of FRS on the sleep status of base stations can be seen in Figure 6, which displays total power and the partition of it that results from sleeping base stations.

Interestingly, at a very low occupancy (0.01%), P_{sleep} is nearly equal in NRS and FRS. The reason for this might be an obvious one: 0.01% of the Dutch population amounts to around 1800 UEs. This number is far smaller than the total number of base stations (around 20,000). Therefore it is likely that almost every UE gets its own BS, and therefore there is no significant difference between the two strategies.

At more realistic loads, the difference becomes clearer. In general, we can observe that a higher P_{sleep} correlates to a lower P_{bs}. This occurs because base stations in sleep mode require far less power than those that are not. At higher loads, P_{amp} is so high that it is able to bridge the difference made by putting BSs in the sleep state.

The total gains of just applying FRS are best observed in Figure 3. From 0.25% to 0.75% of the population being an active UE, we can observe a difference between **2.4MW** and **2.1MW**, or a reduction between **23%** and **17%** from the wattage of NRS. This is a significant difference, yet we had expected it to be larger. We have a few explanations for why FRS performs as it does.

1. Sleeping BSs still require power. The best FRS can do is put a BS in sleep mode. In our simulation, we do not completely power off a BS. The higher coverage of FRS probably makes a number of BSs redundant, and turning them off would save more energy. From Figure 6, which shows what part of the total power is caused by sleeping BSs in various scenarios for NRS and FRS, we see that in FRS, there are more redundant BSs; we achieve the same throughput with more sleeping BSs.

2. BSs have limited resources. Network coverage is an important factor, but we must also consider that there must be available bandwidth and transmit power for a connection to take place. It would not be economical for MNOs to construct resources for a far greater number of UEs than they predicts to have. Therefore MNOs likely have a network that is specifically designed to handle their portion of the population (1/3 of the active UEs). When a BS does run out of resources, a UE is still forced to connect to a different one, reducing P_{sleep} and increasing P_{bs}.

3. In our implementation of FRS, BSs are still limited to using their assigned frequency bands. These are dependent on the MNO that owns the BS. We cannot say with certainty how this affects the results, but it is likely that allowing BSs to operate on more frequencies would further improve the energy efficiency of FRS.

4. The algorithm that maximizes P_{sleep} in our model does not work optimally. At higher network occupancy, the greedy approach of putting as many BSs as possible to sleep fails. A more sophisticated algorithm should be able to keep the total wattage of FRS below or equal to that of NRS at all loads. The reason for this is that NRS only puts restraints on the organisation of the network. Without these restraints, we should still be able to simulate NRS exactly, and thus we should be able to at least replicate its performance with FRS in any situation.

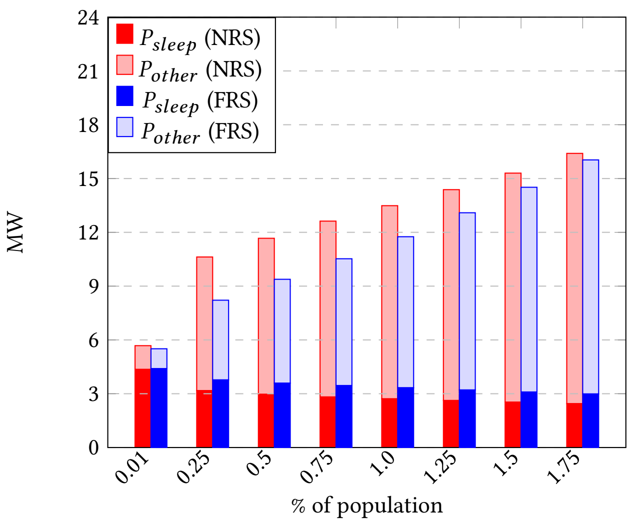

Fig. 6. Sleep wattage and wattage from other causes for both NRS and FRS

5 CONCLUSION

MNOs in the Netherlands currently practise no large-scale forms of resource sharing. A need for competition in the cellular network market is the main reason for this; though other nations have already decided that the benefits of active sharing weigh up to the downside of allowing MNO's to work together. Even with our rather naive implementation of FRS, significant improvements can be made with relation to energy efficiency. If 0.25% of the population is active, we can reduce the total wattage of the network by 23%, and at 0.75% of the population, the reduction is still 17%. A well executed redesign of the whole shared network, not limited by current frequency spectrum divisions, would result in benefits for which our results with FRS are only the baseline. Resource sharing can thus greatly improve the energy efficiency of the Dutch cellular network, but the exact extent entirely depends on how well it is executed.

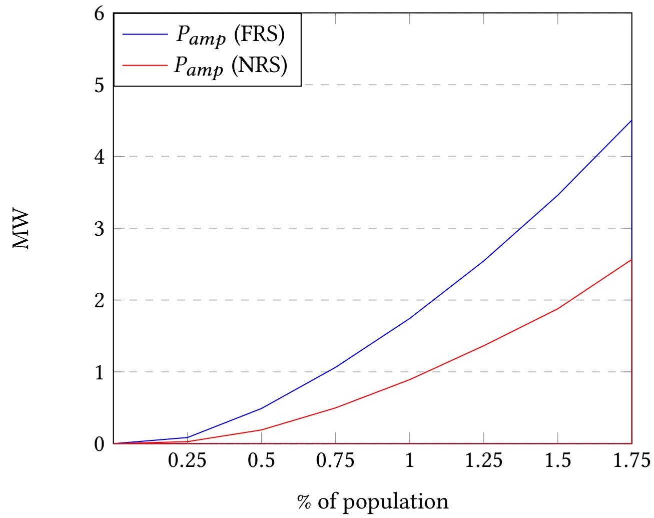

Fig. 7. Total amplifier power for NRS and FRS

6 DISCUSSION

In the design of our model we had to make several compromises to the realism of our simulation. These simplifications can have an effect on the result of our research. There are a few simplifications that should be discussed especially.

1. The choice to exclude interference likely has an effect on the outcome of our simulations. Especially at higher network saturation, it is expected that the interference factor will play a larger role. Therefore the results of our simulator at higher loads should be interpreted as less reliable. It is difficult to predict exactly what kind of a difference this makes.

2. Algorithms for optimizing sleep modes in base stations are as of yet not very well described. Therefore we designed a greedy algorithm of our own. It simply maximizes the number of sleeping base stations at a cost of a higher amplifier power. It might well be that the algorithm that is used in reality is different and thus yields different results.

3. Some constants used in this paper are likely aged or simply not accurate. Base station technology is constantly evolving, and technical details about the actual components used are not public. This means we have to base our assumptions on the findings of previous research, and on educated guesses to the state of the technology.

4. We chose to include the 5G network in our simulation, but given that it's a newer technology, we found that not as much research has been conducted regarding its performance. It could therefore be the case that the model is less well-adapted for 5G base stations.

5. The other abstractions that were mentioned, such as the resource allocation scheme, the base station selection algorithm, and resource multiplexing, will also have had a certain effect on our results. Once again, this effect is difficult to quantify.

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