Analysing the resilience of 5G networks in the Netherlands

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ABSTRACT

Cellular networks are important for people to contact others and access information. This is especially the case during a disaster when people try to reach emergency services and obtain information. During disasters part of the cellular network can be affected by base stations failing. To make the cellular network more resilient in the case of disasters, we must first analyse the resilience. Previous studies that analyse the resilience of cellular networks have been scarce especially for 5G. In this paper we propose a model of 5G systems that is used to analyse the current Dutch cellular network. We also create a model for the effect of high frequency waves (mmWaves) deployment and analyse the impact it would have on the resilience. We show that larger cities are more resilient for disasters and that mmWave deployment can improve the satisfaction of connected users during disaster.

Keywords

5G, mmWave, cellular network, mobile network, resilience

1. INTRODUCTION

Mobile cellular networks are an important part of infrastructure. Many people use these networks, from contact with other people (e.g. phone calls) to a connection to the internet.

The network can be affected by disaster by having base stations (BSs), the connection point to the network, becoming unavailable. This could cause people to lose connection to the network during a situation where it is highly beneficial to have this connection, for example to contact emergency services of your location or find relevant information about the situation.

With the introduction of 5G there is also the ability to use mmWaves [1]. These mmWaves increase the bandwidth and speed of the cellular network but have a smaller range and the signal has higher attenuation [1, 2]. This also introduces the issue that rain can have an impact on the resilience of the cellular network, especially when users and applications use the bandwidth offered by mmWave technologies.

To know the effects of these scenarios, we analyse the resilience of the network under these failures. Resilience in this paper is understood similar to [3, 4] as "the ability of the network to provide acceptable levels of service while challenges, such as natural disasters or heavy rainfall, happen".

In this research we add 5G and mmWave models to an existing network resilience simulator [5]. We also extend the simulator with more precise BS information [6]. We then analyse how resilient the network is in different regions in the Netherlands. We also study the impact of adding mmWave channels on the resilience of the network. With the analysis we answer the following questions:

RQ1: How resilient is the current network in different regions in the Netherlands?

RQ2: What is the effect of mmWave deployment on the resilience of the network?

This research contributes by creating a simulator for analysing the resilience of 5G networks. We also provide an analysis of the resilience of the current network and analyse the effect of mmWave deployment on resilience of the network. The analysis shows that resilience is better in larger cities and that mmWave deployment increases user satisfaction.

The remainder of this paper is organized as follows. In Section 2 related work is discussed. In Section 3 we discuss the methods with which we answer our questions. In Section 4 the results of the analysis are shown. In Section 5 discusses shortcomings of this research and in Section 6 we conclude the results.

2. RELATED WORK

Research into the resilience of the Dutch mobile network was performed by Janssen [5]. This research first analysed potential resilience metrics and potential risks. They then created a simulation to perform an analysis on the resilience of several Dutch cities. This simulation was limited by the use of crowdsourced data and the assumption that all BSs are LTE. The research finds that Middelburg has the weakest resilience and Amsterdam the strongest from all tested cities. They also find a relation between the number of connected users per BS and the satisfaction.

Previous research studied the effect of seismic activity in an urban environment [7]. In this research they created a model for the network infrastructure based on crowdsourced data. In their analysis they also take into account how the BSs are connected to each other and the wired network but their model of the wireless connection is more general since they did not have information on the type

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of radio for a BS. For throughput calculations as part of their model they assume LTE channels.

Other research on the effect of disasters on the reliability of networks created a simple model based on crowdsourced data on cellular and Wi-Fi access points [8]. Their model assumes an effective range for the access points. They then analyse methods that could improve the number of isolated users in their scenario.

3. METHOD

In order to determine the resilience of the mobile network we created a simulator [9]. In this section we describe the models used in the simulator as well as the assumptions that were made.

3.1 Simulation

The simulator simulates the resilience of an area. This area can consist of one rectangle for a rural macro cell (RMa), one rectangle for urban macro cell (UMa) and one rectangle for urban micro cell (UMi). For these rectangles the UMi rectangle is inside the UMa rectangle and the UMa rectangle is within the RMa rectangle. A macro cell are BSs that have a large range and are used in less dense areas, where micro cells have a smaller range used in denser areas and are closer together.

All the BSs within the area are loaded from a dataset [6] containing information on the BSs. Each BS in the dataset can have multiple channels each with multiple antennas. For each of these antennas the transmission power and height is known. For simplification the simulator only uses the power of only one of the antennas for each channel. The height is set for the BS and is taken from the height of one of the antennas.

A channel is a frequency band on which users can connect to a BS. This channel has a maximum bandwidth of 20 MHz. The channel can be split such that multiple users can use the channel. This bandwidth can be subdivided into the following bandwidths: [20, 15, 10, 5, 3, 1.4] MHz [10].

Within the total area user equipment (UE) is placed according to a uniform distribution. The number of UE is based on the population in the area [11]. Since not everybody living in the area uses the mobile network at the same time it is assumed only 0.7% of the population uses the network [5]. Besides a position each user will also have a requested data rate. This data rate is random between 10 and 100 Mbps to simulate different traffic types, e.g. web browsing or video streaming.

A user will try to connect to the closest BS. If that is not possible it will try the next BS. They will continue to try connecting to all BSs within 5000m. If the user cannot connect to a BS the user is an isolated user. When connecting to a BS a channel is chosen that the user can connect to. This is the channel with the most bandwidth left and when there are more with the same bandwidth the channel with the best productivity. The productivity of the channel is determined by checking the requested data rate against the received data rate for all already connected users. e.g. if two channels have 5MHz of bandwidth left but one has a user wanting 20 MHz but he only receives 15MHz, and on the other channel all users receive more than requested the second channel is chosen. Reasons a user can not connect are when the received power is lower than -80 dBm. This causes the signal to be too low to correctly receive and decode data [12, 13]. Another reason is that the BS is already fully utilized.

To determine the bandwidth a user needs to fulfil the requested data rate, the Shannon capacity is used. This is given by

$$C = B\log_2(1+SNR), \tag{1}$$

where C is the capacity of the connection in Mbps, B is the bandwidth in MHz and SNR is the signal-to-noise ratio. The signal-to-noise ratio is calculated using

$$SNR = \frac{P_{signal}}{P_{noise}} \tag{2}$$

where P_{signal} is the received signal strength and P_{noise} is the noise level. For the simulation the noise level is assumed to be -100 dBm [5]. In order to find the received power

$$P_{rx} = P_{tx} - \max(PL - G_{tx} - G_{rx}, MCL) \tag{3}$$

is used for LTE [5] and

$$P_{rx} = P_{tx} - PL + G_{tx} + G_{rx} \tag{4}$$

for 5G NR. In these equations PL is the path loss in dB (see § 3.2.1), G_{tx} is the antenna gain of the transmitter and G_{rx} the antenna gain of the receiver and MCL the minimum coupling loss which is the minimal loss for the path. The signal-to-noise ratio from Equation 2 requires a linear power, so the assumed noise level and calculated received power are transformed from dBm to mW using $P_{mW} = 10^{P_{dB}/10}$. The antenna gain for the receiver is assumed to be 0 dBm and the minimum coupling loss is assumed to be 70 dBm. The antenna gain for the transmitter is assumed to be 15 dBm but can be increased with beam forming (see § 3.2.3).

3.2 Channel model

The model for channels consist of several parts. The first is the path loss. This is the loss of signal power over a certain path. Next is the line of sight probability. This is the probability that the UE and BS are within line of sight. This is important since this changes the path loss. The last part is beam forming. This is a technique where antennas are aimed at a specific location instead of being omnidirectional. This is assumed to be used for mmWave only.

The distances used in the models are defined in Figure 1. The d_{2D} is the distance between the ground points of the BS and UE. d_{3D} is the distance in 3D between the antennas of the BS and UE.

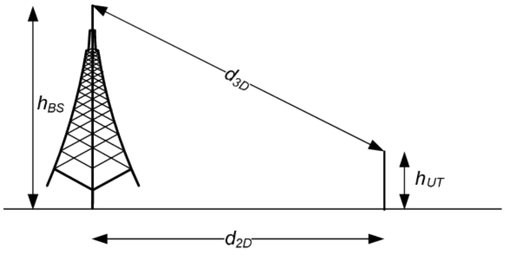


Figure 1. Distances [14]

3.2.1 *Path Loss Model*

For the path loss two models are used: one for LTE and one for 5G NR.

For LTE the path loss defined by Janssen [5] is used. This path loss model is defined for the UMa area, but is used for all the areas in this simulator.

The path loss for 5G NR is based on the model provided by 3GPP [14]. The 3GPP path loss model defines the path loss for several different situations. In this paper the models for RMa, UMa and UMi are used, with different models for the line of sight (LoS) and no line of sight (NLoS) scenarios. Some variables from the model are known from the data from *Antennebureau* [6]. For the others the following values are taken: For the UE a constant height is taken of 1.5 meters. The average building height is only used in rural areas, here it is assumed the average height of buildings is two stories or 7 meters. For the average street width a width of 10 meters was taken.

3.2.2 LoS Probability Model

To determine the use of the LoS or NLoS model for path loss the probability of LoS is needed. This probability is calculated using the following equations based on the environment [14]:

$$Pr_{LOS-RMa} = \begin{cases} 1, & d_{2D} \leq 10m \\ \exp(-\frac{d_{2D}-10}{1000}), & 10m < d_{2D} \end{cases} \tag{5}$$

$$Pr_{LOS-UMa} = \begin{cases} 1, & d_{2D} \leq 18m \\ \frac{18}{d_{2D}} + \exp(-\frac{d_{2D}}{36})(1 - \frac{18}{d_{2D}}), & 18m < d_{2D} \end{cases} \tag{6}$$

$$Pr_{LOS-UMi} = \begin{cases} 1, & d_{2D} \leq 18m \\ Pr^{'}, & 18m < d_{2D} \end{cases} \tag{7}$$

with

$$\begin{aligned} Pr^{'} = [&\frac{18}{d_{2D}} + \exp(-\frac{d_{2D}}{63})(1 - \frac{18}{d_{2D}})] \\ &(1 + C^{'}(h_{UE})\frac{5}{4}(\frac{d_{2D}}{100})\exp(-\frac{d_{2D}}{150})) \end{aligned}$$

where

$$C^{'}(h_{UE}) = \begin{cases} 0, & h_{UE} \leq 13m \\ (\frac{h_{UE}-13}{10})^{1.5}, & 13m < h_{UE} \leq 23m. \end{cases}$$

3.2.3 Beam Forming Model

Beam forming is a technique used to improve the signal by making the signal more directional. For beam forming it is assumed that the antennas are perfectly aligned with the UE. This is modelled by adding a constant gain of 10dB [15] to the transmission gain of the antenna. UE cannot use the same beam and beams cannot be directed in the same direction as other beams. To prevent this each beam has a 10 degree cone around it. Any UE in that cone cannot connect to the same channel.

3.3 mmWave model

Since mmWave is not yet deployed in the Netherlands information on the BSs and antenna specifications is unknown. To model the effects of mmWave a number of 5G NR BSs located in urban areas are assumed to also have mmWave capabilities. For mmWaves it is assumed the transmission power is 60 dBm and the frequency is 26 GHz [16]. Beam forming is applied to mmWave channels. For path loss the model for 5G NR applies.

3.4 Resilience Metrics

To determine the resilience of the network two metrics are used [5]. These are be discussed here.

Quality of service

The quality of service (QoS) is determined based on the average satisfaction of all users. This is calculated as follows:

$$S = \frac{\sum_{i=0}^{\#users} \frac{C_i}{R_i}}{\#users}$$

where S is the average satisfaction, C_i the received data rate and R_i the requested data rate of a user.

Isolated users

Isolated users are users that could not connect to a BS.

3.5 Test Scenarios

To determine the resilience of the network two scenarios are tested [5].

Natural Disaster

This scenario simulates the impact of natural disaster on the cellular network. A disaster epicentre is randomly chosen within the simulation area. The area effected by the natural disaster starts at 0m for a baseline and increases by 1000m up until 9000m. In this scenario BSs will fail based on a probability based on the distance to the epicentre.

$$Pr_{failure} = (\frac{d_{BS}}{r})^2$$

where d_{BS} is the distance between the BS and epicentre and r the radius of the effected area.

Natural disaster with power outage

This scenario is similar to the natural disaster. The difference is that in this scenario all BSs within the effected area will fail.

These scenarios are tested with 0%, 50%, and 100% mmWave deployment. The percentage mmWave deployment determines the chance a BS has mmWave capabilities. Since users and disasters are placed at random and the channel models contain randomness each scenario is run several times. For each user distribution a scenario is performed 75 times. Users are redistributed 4 times. This results in a total of 300 simulations for each scenario.

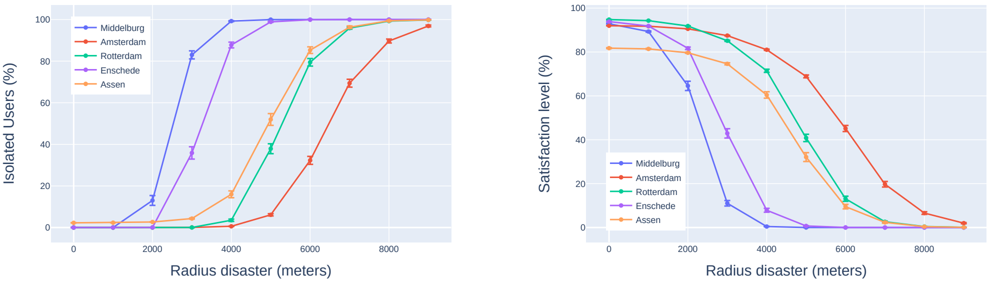
4. RESULTS

In this section the results of running the simulator will be discussed. The figures shown include a 95% confidence interval represented by the bars around the data points.

4.1 LTE and 5G resilience

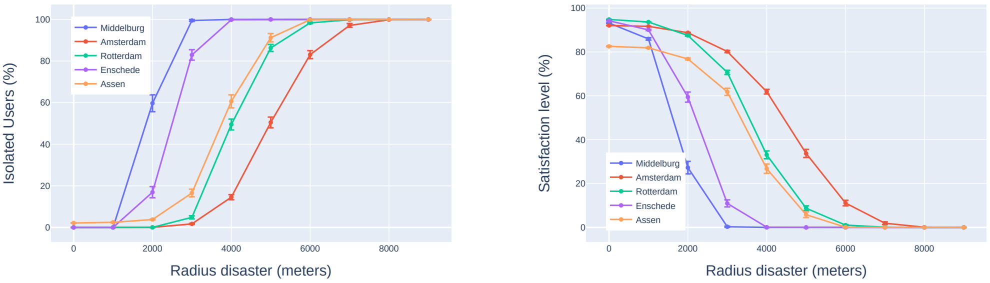
First the simulator was run on the current deployment of LTE and NR BSs in the Netherlands. The results of a disaster can be seen in Figure 2. For a disaster with power outage the results are in Figure 3. In these figures it can be seen that the number of isolated users as well as the satisfaction level have a steeper curve that starts earlier for a disaster with power outage. This is to be expected since the number of active BSs and available channels is lower in the disaster with power outage scenario.

For both the scenarios Middelburg has the weakest resilience and Amsterdam the strongest. In the results it seems like the cities/areas with a larger population are more resilient than areas with less people. This could be due to the larger number of BSs resulting in more BSs being available right outside the disaster area. Additionally the selected area for Middelburg is the smallest, which means that with a larger disaster radius the probability of the disaster completely covering the area increases.



(a) Isolated users (b) Satisfaction level

Figure 2. Impact of a disaster on the current network



(a) Isolated users (b) Satisfaction level

Figure 3. Impact of a disaster with power outage on the current network

An interesting result is the area of Assen. In this area even without a disaster there are isolated users and a low satisfaction. This could be because it is the only area with a rural area around the town. In this area the number of BSs is low, but in the simulation UEs are distributed uniformly across the whole area. This user distribution results in a unrealistic number of users in the rural area thus resulting in isolated users and lower satisfaction.

4.2 mmWave resilience

Next the simulator was run with different levels of mmWave deployment as described in § 3.5.

In Figure 4 and 5 the difference between the different levels of mmWave deployment can be seen for a disaster scenario in Assen and Amsterdam.

In Assen the number of isolated users is similar for 0% and 50% mmWave deployment. This is likely due to the the existence of a rural area and the number of users in this area. Since mmWave is only deployed in urban areas only the small urban area of Assen benefits from mmWave deployment in this simulation. The satisfaction in Assen does increase but with an increase in disaster radius this increase becomes smaller. For 100% mmWave deployment the number of isolated users is unusually high for no or small disasters. This can also be observed in the satisfaction level. This might be due to the method of choosing a channel where UE connects to. The channel choice is based on the best available channel which is likely to be the mmWave channel. After the choice of channel, the path loss is calculated which can result in a failed connection to the channel and with it a failed connection to the BS. It is however strange that Assen is the only area that shows this behaviour. A possible explanation for this is the small urban area of Assen and thus the limited number of mmWave capable BSs.

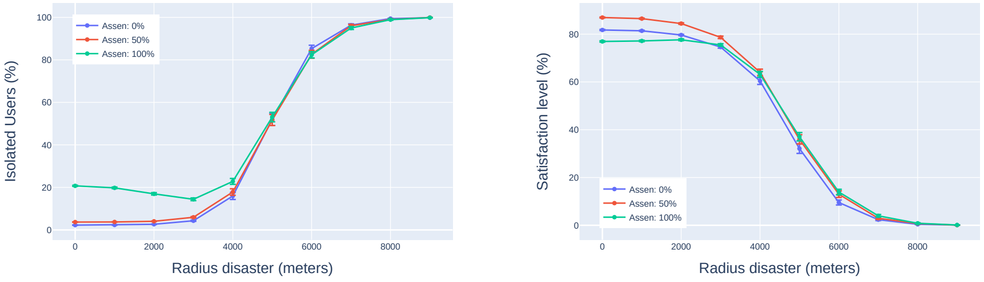
For Amsterdam it can be seen that the satisfaction is higher when mmWave is deployed. This could be due to mmWave antennas having beam forming, which makes it that users connected to a mmWave channel do not receive less bandwidth thus not reducing their satisfaction level. The number of isolated users was decreased, likely due to an increase in the number of available channels. It can also be seen that the decrease in isolated users and increase of satisfaction are greater when going from 0% mmWave deployment to 50% than from 50% to 100%.

The other cities showed similar patterns to Amsterdam. With a small increase in satisfaction and a small decrease in the number of isolated users when deploying mmWave.

In Figure 6, 7, and 8 the difference between the different levels of mmWave deployment can be seen for a disaster scenario with power outage for Assen, Amsterdam and Enschede.

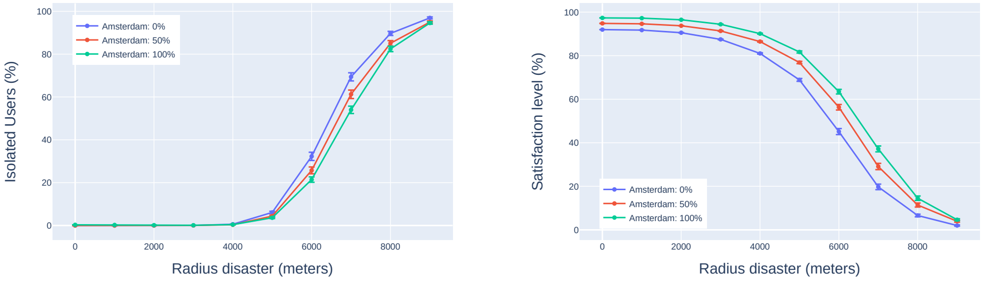
In Assen adding mmWave increases the number of isolated users when a disaster with power outage occurs. The satisfaction is also lower when mmWave is deployed. A similar pattern is seen as in Figure 4 where the 100% mmWave deployment has a large number of isolated users for no to small disasters.

In Amsterdam the effect of a disaster with power outage



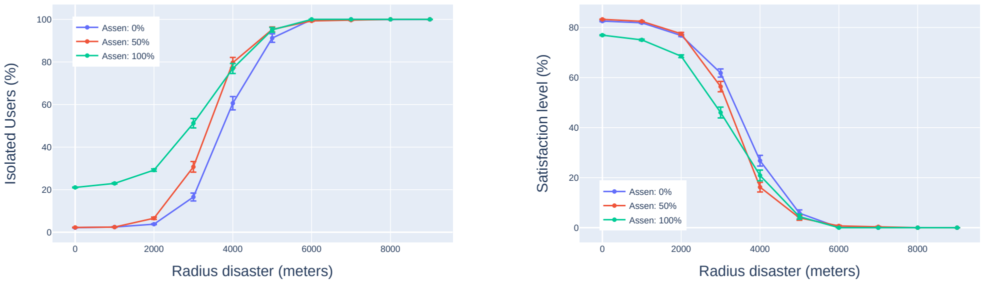
(a) Isolated users (b) Satisfaction level

Figure 4. Impact of a disaster in Assen for different mmWave deployment levels



(a) Isolated users (b) Satisfaction level

Figure 5. Impact of a disaster in Amsterdam for different mmWave deployment levels



(a) Isolated users (b) Satisfaction level

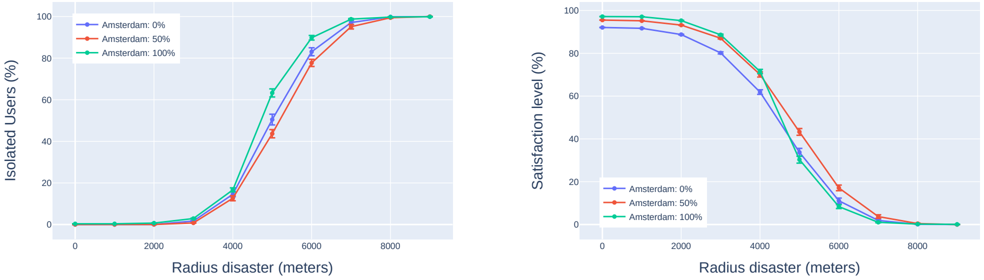
Figure 6. Impact of a disaster with power outage in Assen for different mmWave deployment levels

is similar to the disaster without power outage (Figure 5) for 0% and 50% mmWave deployment. However when 100% of the BSs support mmWave the number of isolated users is larger. The satisfaction level is higher for smaller disasters but drops faster than for the other deployment levels such that after a disaster radius of 4000 meter the satisfaction is lower for 100% mmWave deployment than for 0%.

For the Enschede area the number of isolated users does not significantly differ with different mmWave deployments. This is expected since all BSs in the disaster radius fail, thus mmWave will also fail. Since mmWave has a shorter range it has less chance to get a connection compared to the lower frequencies of 5G NR and LTE. The satisfaction level is slightly increased with more mmWave deployment as shown in Figure 4.2. The increase in satisfaction can be explained by the fact that mmWave channels allow for higher bandwidth, so any user that can still connect to such a channel will have a high satisfaction.

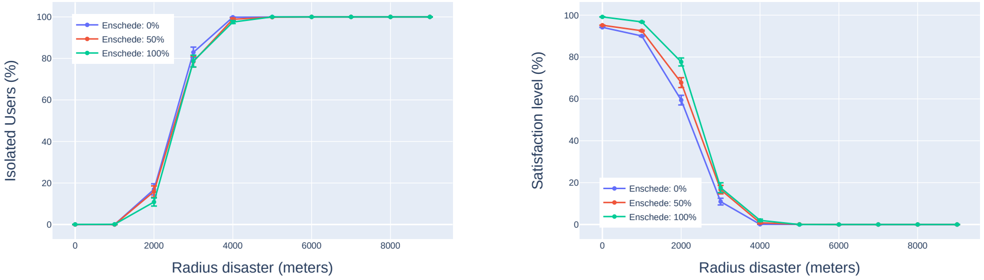
The other cities showed similar patterns to Enschede, with no significant difference in isolated users and a increase of satisfaction.

5. DISCUSSION



(a) Isolated users (b) Satisfaction level

Figure 7. Impact of a disaster with power outage in Amsterdam for different mmWave deployment levels



(a) Isolated users (b) Satisfaction level

Figure 8. Impact of a disaster with power outage in Enschede for different mmWave deployment levels

Several improvements could be added to the simulator to provide a more realistic analysis.

The first is that atmospheric attenuation is not used within the simulation. This is especially relevant for mmWave since mmWave is impacted by rain [2, 17]. This could reduce the effect on satisfaction of mmWave deployment seen in this paper.

Second the distribution of UE could be improved. Using a uniform distribution for UE location, when both rural and urban environments are present, the results might not represent reality. For example Assen consists of a small urban area and a larger rural area surrounding the city. With the uniform distribution the rural area has the same user density as the urban area in the simulator, where in real life the city would likely have more users than the rural area. The problem of the uniform distribution can be seen in the results for Assen where even without disaster there are isolated users (see Figure 2 and 3).

Another part is that only BSs within the area are loaded. This means BSs just outside the area are not taken into account in the simulation. With smaller areas this could make the results of this paper seem worse than in real scenarios since users cannot connect to BSs outside the simulation area that might not be effected by the disaster. It could also mean that users located at the border of the area in the simulator have to connect to a BS that is not the closest BS.

Furthermore the simulation only uses LTE and 5G NR BSs. Older mobile technologies have not been taken into account and could result in improvements to resilience due to more channels being available.

It is also assumed that all UE can connect to every BS. This is not always the case due to different BSs being owned by different carriers. Customers from one carrier normally do not connect to the BSs of other carriers.

As can be seen in the results on mmWave deployment for Assen for disasters as seen in Figure 4 and Amsterdam for disasters with power outage seen in Figure 7 is that there are more isolated users with mmWave deployment than without. As stated this is likely due to the method used for connecting UE to BSs. Since only the best available channel is used for a connection to a BS this is likely to be the mmWave channel. The mmWave channel has a high frequency so its path loss will be larger and the chance of connection lower. Changing the simulator to then try to connect to another channel on the BS will likely change these results.

We also use 0.7% of the population as the number of users using the network. The number of users using the network might be different. An interesting addition to this research could be to research the effect of different user densities on the resilience of the network.

6. CONCLUSION

In this paper the resilience of the current mobile LTE and 5G NR network is analysed as well as the effect of mmWave deployment on the resilience.

In the current network Amsterdam is the most resilient against disasters and Middelburg the least resilient. We found a connection between the size of the population in a city and its resilience, where cities with larger populations are more resilient against disasters. That cities with larger populations are more resilient is likely due to a larger number of BSs. The resilience of the cities of Middelburg and Enschede are low since at respectively 3000 and 4000 meter disaster radius more than 80% of users were isolated. The other cities fared better with disaster radii needing to be larger than 6000 meters before 80% of the users were isolated.

When comparing the results of this paper with the previous work [5], we found that for both disaster with and without power outage the resilience was significantly worst in our simulation. A similar pattern can be found though with the cities with larger population being more resilient against disasters.

During a disaster without power outage mmWave deployment decreased the number of isolated users by at most 10%. In Assen the number of isolated users went up when 100% of BSs had mmWave capabilities. Except for Assen the number of isolated users and satisfaction was larger when mmWave was deployed. The difference between 0% and 50% mmWave deployment was larger than for the difference between 50% and 100% mmWave deployment.

During a disaster with power outage Assen (see Figure 6) is negatively impacted by mmWave since the number of isolated users is lower without mmWave deployment and satisfaction is lower or equal to the situation without mmWave deployment. In Amsterdam (see Figure 7) mmWave deployment of 100% shows the same negative impact as in Assen, but 50% mmWave deployment shows a small improvement in both the number of isolated users and satisfaction. For the other simulated cities the mmWave deployment level had no influence on the number of isolated users and increased the satisfaction slightly (as seen in Figure 8).

Both the disaster with and without power outage show that mmWave deployment can improve and deteriorate the number of isolated users. The satisfaction is in most cases improved.

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