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TNO report

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Co-existence of 5G mobile networks with Burum Satellite Access Station operating in C-band

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Achtergrond
Eén van de in Europa aangewezen frequentiebanden voor de introductie van 5G mobiele netwerken is de 3400-3800 MHz band (kortweg aangeduid met de 3,5 GHz band). Deze band maakt echter ook deel uit van de zogenaamde C-band (3400-4200 MHz), een internationale band voor satellietcommunicatie. Naast het gebruik van deze band voor satellietcommunicatie door het Satellite Access Station van Inmarsat in Burum (kortweg aangeduid met Burum SAS) wordt deze ook door de ernaast liggende interceptie-faciliteit van Defensie gebruikt voor inlichtingen-vergaring.

De co-existentie van 5G mobiele netwerken en de interceptiefaciliteit in Burum was eerder al door TNO onderzocht. Op grond van de resultaten van deze studie [1] bleek co-existentie van 5G mobiele netwerken en de interceptiefaciliteit niet mogelijk zonder grote nadelen, waaronder een grote exclusion zone rondom Burum waar geen 5G kan worden ontplooid en een sterk toegenomen productieverlies voor het interceptiestation. Er is daarom door het Kabinet besloten om de mogelijkheden te onderzoeken om de C-band interceptiecapaciteit naar het buitenland te verplaatsen.

Het naast het interceptiestation gelegen Burum SAS maakt echter ook gebruik van een deel van de 3,5 GHz band (3550 - 3676 MHz) voor communicatie met twee geostationaire satellieten en is niet in staat deze buiten het frequentiebereik van de 3,5 GHz-band te gebruiken. Uit een studie van Inmarsat blijkt dat verregaande beperkingen aan de 5G mobiele netwerken zouden moeten worden opgelegd om verstoring van de door Burum SAS ondersteunde satellietdiensten te voorkomen. Deze beperkingen lijken dusdanig restrictief dat 5G mobiele netwerken en Burum SAS hierdoor niet naast elkaar kunnen bestaan in een groot deel van het noorden van Nederland.

Opdracht aan TNO
TNO is gevraagd om een second opinion te verstrekken over deze kwestie en in het bijzonder de mogelijke impact van 5G netwerken op Burum SAS inzichtelijk te maken, aan te geven welke mitigatiemogelijkheden aan Burum SAS en 5G zijde in aanmerking komen om deze impact te reduceren, en te adviseren in hoeverre co-existentie tussen beide applicaties onder toepassing van mitigerende maatregelen, mogelijk en realistisch is. TNO heeft dit onderzoek uitgevoerd, waarbij grote delen van het voorgaande onderzoek (met betrekking tot de interceptiefaciliteit [1]) hergebruikt. De enige verschillen betreffen de technische specificaties, operationele eisen en de beschermingseisen, die voor Burum SAS verschillen van die van de interceptiefaciliteit.

Bevindingen
Aangezien Burum SAS gebruik maakt van een deel van de 3,5 GHz band (namelijk 3550-3676 MHz), zijn twee situaties apart beschouwd:
- het gebruik van de frequentieband 3550-3676 MHz (waarin ook Inmarsat opereert) door 5G mobiele netwerken (hier aangeduid met *co-channel* gebruik) en

- het gebruik van de hiernaast liggende frequentiebanden (3450-3550 MHz en 3676-3750 MHz) door 5G mobile netwerken (hier aangeduid met *adjacent channel* gebruik)

Uit het onderzoek blijkt dat bij adjacent-channel er zonder mitigatiemaatregelen een exclusion zone van 21 km rond Burum nodig, die vrij eenvoudig nog substantieel kan worden verkleind met toepassing van een filter bij Burum SAS.

Bij co-channel gebruik zijn de problemen echter veel groter. Om ook voor de co-channel situatie een exclusion zone van circa 20 km rond Burum te verkrijgen zijn mitigatie-maatregelen nodig die de interferentie met tenminste ca 47 dB verlagen, uitgaande van de gebruikelijke ITU protectiecriteria. Daarbij is alleen de ontplooiing van 5G mobiele netwerken in Nederland beschouwd. De ontplooiing van 5G mobiele netwerken in aangrenzende landen (met name Duitsland) is niet meegenomen in de berekeningen en hierdoor zal in principe een hogere onderdrukking van de interferentie nodig zijn. Bij een gelijke ontplooiing van 5G als in Nederland bestaat de verwachting dat de interferentie ten gevolge van 5G mobiele netwerken in Duitsland bij een exclusion zone groter dan 70 km zelfs dominant kan zijn.

Een aantal mitigatiemaatregelen zijn beschouwd en voornamelijk kwalitatief beoordeeld. Door TNO beschouwde mogelijke mitigatiemaatregelen aan 5G en SAS zijde variëren in effectiviteit (bijdrage aan totale mitigatiedoel), technische volwassenheid (TRL) en structurele business impact. De bevindingen zijn samengevat in onderstaande tabellen weergegeven.

Burum SAS maatregel	Effectiviteit	TRL	Business impact
Lagere beschikbaarheid van satellietdiensten	Matig	Hoog	Hoog
RF scherm	Matig, lage voorspelbaarheid	Matig	Mogelijk
Schotel aanpassingen	Matig	Hoog	Neutraal
Geavanceerde antenneoplossingen	Hoog	Laag	Neutraal
Signaal processing	Onduidelijk	Laag	Neutraal
Notch filtering	Matig	Hoog	Mogelijk

5G maatregel	Effectiviteit	TRL	Business impact
Exclusion zone	Matig (binnen 50 km)	Hoog	Hoog
Conventionele EIRP reductie maatregelen	Matig	Hoog	Hoog
Geavanceerde antennetechnieken	Hoog, lage voorspelbaarheid	Laag	Hoog
Verkeer gerelateerde maatregelen	Laag	Hoog	Matig

Conclusie

Een combinatie van diverse technische maatregelen zou zijn vereist om in de buurt te komen van het mitigatiedoel dat is afgeleid van de impactberekeningen. Op basis van de voorziene mitigatie-uitdaging en hoe die zich op langere termijn nog kan ontwikkelen, en op basis van een overwegend kwalitatieve inschatting van haalbare effectiviteit en consequenties, zijn wij concluderend pessimistisch over de praktische haalbaarheid van een co-channel co-existentie arrangement tussen 5G netwerken en Burum SAS.

Contents

Appendices

1 Introduction

1.1 Background

One of the designated frequency bands in Europe for the introduction of 5G based mobile networks is the 3400 to 3800 MHz band (abbreviated ad 3.5 GHz band). This band is also part of the so called C-band, an international band for satellite communications, which is defined between 3400 and 4200 MHz. Besides for satellite communications by Burum SAS (Satellite Access Station of Inmarsat), it is also used by the Burum Interception Facility, to gather relevant intelligence data for the Dutch government.

The co-existence of the Burum Interception Facility with 5G mobile networks has been studied before [1]. The results of this study indicated that co-existence of 5G networks and the Burum Interception Facility is not possible without a large exclusion zone in which 5G mobile networks cannot operate and an increased production loss for the Burum Interception Facility. Therefore the Cabinet has decided to investigate the possibilities to relocate the C-band capability of the Burum Interception Facility to locations outside The Netherlands.

Burum SAS, co-located with the Burum Interception Facility, is however also using a portion of the 3.5 GHz band (3550-3676 MHz) for the feeder links with two geostationary satellites. These satellites do not offer the flexibility to use another portion of the spectrum outside the 3.5 GHz band for the feeder links. A study from Inmarsat shows that co-existence of Burum SAS and 5G mobile networks is only possible with serious restrictions, which do not seem to allow the co-existence of Burum SAS and 5G mobile networks in a large part in the north of The Netherlands. TNO has been asked to provide a second and independent opinion on this matter.

TNO conducted the investigation of which the results are contained in this report. We leveraged relevant assumptions and insights obtained during the previous study [1] concerning the Burum Interception Facility.The only differences between this study and the previous one concerns the technical specifications and operational requirements of Burum SAS and the protection requirements. It is of importance to note that only the deployment of 5G mobile networks in The Netherlands is taken into account. The impact of 5G deployment in neighbouring countries (like Germany) will only be indicated.

In order to keep this report short and readable, the focus will be on the differences with the previous study and its consequences. For all aspects remaining the same, the reader is referred to the previous study in which they have been discussed in detail. The only exception is made for the 5G deployment scenarios. For a quick overview, their description has been added in Appendix A. Of these scenarios the most developed deployment scenario 3e (nationwide, capacity, evolved; late stage, 2028[1]) has been selected for this study.

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[1] As the prediction uncertainty regarding likely mobile network deployments and their utilization grows over time, our forecast does not extend beyond 2028.

1.2 Structure of this report

In Chapter 2, Burum SAS and its technical specifications and operational requirements as well as the protection requirements are discussed.

In Chapter 3, the results of co-existence calculations are presented and analysed. They are in the form of the mitigation effort needed to achieve a given exclusion distance. The exclusion distance (in km) being defined as the distance from Burum SAS within which no deployment of 5G is allowed, and the mitigation effort being defined as the reduction (in dB) of the total 5G interference level received at the LNA's of the dishes at SAS Burum which needs to be achieved by taking (additional) mitigation measures.

In Chapter 4, the available mitigation measures are discussed to achieve the mitigation effort. This concerns mitigation measures which can be taken in 5G networks as well as at Burum SAS.

Chapter 5 contains the final analysis and conclusion.

2 Burum Satellite Access Station (SAS)

2.1 General

The C-band is among the first bands being used for satellite communications. Its key features are that it allows for wide area coverage and that it is extremely resilient to severe weather conditions like heavy rain. The clear sky noise temperature in C-band is also very low, resulting in terminals with very low noise levels compared to other frequency bands. This results in terminals allowing robust communications at low signal levels.

Inmarsat is using the C-band for its feeder and Telemetry, Tracking, and Command (TT&C) links in their mobile satellite communication systems. In this case, the communication between user equipment and the satellite (user link) occurs in L-band and from the satellite in space it is redirected down to the gateway station in Burum in C-band (feeder link). When the communication arrives at the gateway station in Burum it can be either routed into a fixed terrestrial telecommunication network or back via the satellite to another mobile satellite communication user.

Inmarsat provides various services, supporting aeronautical (Aero H), land-based (BGAN, SPS[2]) as well as sea-based (Inmarsat-C) users.

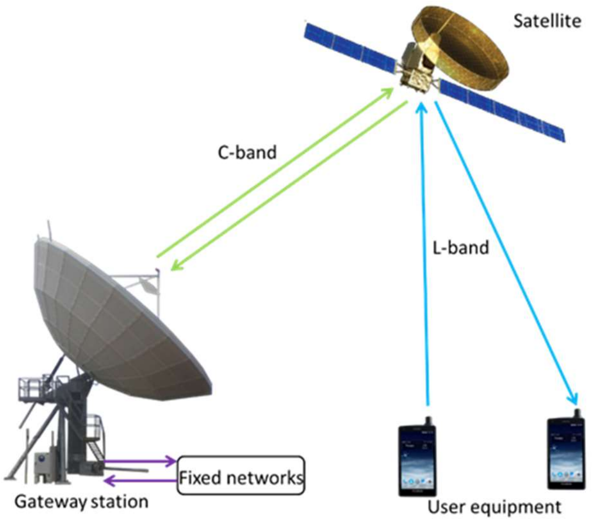

Figure 2.1: Mobile satellite communications system (green= feeder link, blue=user link).

Inmarsat’s L-band satellites also carry safety service traffic as the only operator authorized to do so by the International Maritime Organisation (IMO) and additionally supported by International Civil Aeronautical Organization (ICAO) as well as key security and critical infrastructure services.

The C-band will remain to be used for the feeder links with current satellites until 2035-2042 (depending on actual satellite life time).

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[2] Satellite Phone Services (hand-held)

2.2 Burum SAS details

2.2.1 Location

The Satellite Access Station in Burum (Burum SAS) is located near Burum as shown in the figure below.

Figure 2.1: Location of SAS Burum (top-left) near Burum (bottom-right).

2.2.2 *Operational*

Burum SAS is using two dishes to receive the satellite signals in the 3550-3676 MHz band from two geostationary satellites:

- Alphasat (located at 25^0E) and
- Inmarsat-4F2 (located at 64^0E)

Figure 2.2: Burum SAS (top marked area) and Burum Interception Facility (bottom left marked area).

2.2.3 *Technical*

The main technical parameters of the satellite dishes used to receive the satellite signals from Alphasat and Inmarsat-4F2 are[3] :

Antenna diameter D:	13.10 m
Efficiency η[4]:	0.72
System noise temperature T_S[5]:	79 K
Antenna height (h)[6]:	10 m

2.3 Protection criteria

To determine whether or not Inmarsat satellite services require protection[7] against interference originating from 5G mobile networks, the criteria given in Recommendation ITU-R SF.1006 and ITU-R Report S.2368 are used. These documents describe the following three criteria to be met:

1. Long-term criterion

The total interference level shall not exceed 10% of the system noise level for more than 20% of the time. This criterion is used to ensure that the minimum desired quality of the received satellite signals is met for most of the time. The long-term criterion is only applicable in the operating frequency band of Burum SAS (3550-3676 MHz).

2. Short-term criterion

The interference level shall not exceed the maximum permissible interference level for more than 0.005% of the time (maximum permissible interference as defined in SF.1006, with fade margin $M_S = 2$ dB; link noise contribution by the satellite transponder including uplink noise $N_L = 1$ dB and thermal noise equivalence factor for interfering emissions W = 0 dB). This criterion is used to ensure that the reduction in availability of the satellite links due to interference is limited to 0.005% of the time. The short-term criterion is only applicable in the operating frequency band of Burum SAS (3550-3676 MHz).

3. Blocking criterion

The total received interference power in the 3400-3800 MHz band, shall not exceed -61 dBm. This criterion is used to prevent the receiver's Low Noise Amplifier (LNA) from being driven outside its dynamic range where it exhibits non-linear behaviour (resulting in intermodulation products and gain compression). Since the LNA is a wideband device, intended to have a low noise figure and flat frequency response over the frequency band of 3400-4200 MHz, this blocking criterion is applicable in the total downlink frequency band of 3400-4200 MHz.

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[3] "*Inmarsat System Technical Parameters and derivation of PDF limits_Septem.._New.docx*" and *"GDST_13p10mCA_C-band ITU-580-732_Wide_Angle_Patterns.pdf"*, Inmarsat documents.

[4] Derived from antenna gain of 52.5 dBi at 3.625 GHz

[5] Based on ITU-R Report S.2368

[6] Antenna dish centre height above ground level.

[7] And if so, how much protection.

3 Results of co-existence calculations

3.1 Introduction

As shown in Figure 3.1, there are two 50 MHz wide frequency bands at each end of the spectrum which are meant for local deployments of 5G (like for instance on an airport or in a harbour). These are not taken into account, due to the yet many unknowns (number of local deployments, their locations, co-existence requirements for local 5G deployments and radars operating below 3400 MHz as well as regular satcom systems operating above 3800 MHz)[8].

The focus will be on the frequency band between 3450 and 3750 MHz. Within this 300 MHz wide band, intended for nation-wide deployment of 5G mobile networks, Inmarsat is operating in the 3550-3676 MHz band. For this reason, the co-existence of 5G mobile networks and Burum SAS has to consider two different cases:

1. Co-existence of Burum SAS and 5G networks outside the frequency range 3550-3676 MHz. In this case, the 5G interference experienced at Burum SAS is received in adjacent channels (of the band in which Burum SAS operates) and only the blocking criterion as mentioned in section 2.1.3 is applicable.
2. Co-existence of Burum SAS and 5G in the frequency range 3550-3676 MHz In this case, the 5G interference experienced at Burum SAS is in the same channel as in which it operates (co-channel interference) and all three criteria, as mentioned in section 2.1.3, are applicable.

Figure 3.1: 3.5 GHz band

For each case, the exclusion distance as function of the required mitigation effort has been calculated. The exclusion distance is defined as the area around Burum SAS within which no deployment of 5G is allowed, while the mitigation effort is defined as the reduction in dB of the total 5G interference level received at the LNA of the dishes at SAS Burum which is achieved by taking additional mitigation measures. The mitigation measures themselves, which can be applied to obtain the required mitigation effort, are discussed in the next chapter together with their feasibility and other relevant aspects.

The 5G deployment scenario used in our calculations is specified in Annex 1.

3.2 Adjacent channel interference

To avoid the blocking criterion to be exceeded, an exclusion distance of 21 km is required (without the need for any mitigation effort). It can be reduced substantially by applying a filter before the LNA of the dishes at Burum SAS (discussed in the next chapter, section 4.1).

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[8] Neglecting the two 50 MHz bands for local deployment of 5G will only have a very limited impact as will be shown in Chapter 4.

3.3 Co-channel interference

Without any mitigation effort, an exclusion distance is required of:
- 21 km to meet the blocking criterion,
- 63 km to meet the long term criterion and
- 287 km to meet the short term criterion.

With a mitigation effort the exclusion distance can be reduced as shown in the figure below. In all cases, the exclusion distance which can be achieved for a given mitigation effort is determined by the short term criterion which is the most restrictive. So, for example to achieve an exclusion distance of 20 km, allowing 5G deployment in the city of Groningen, a substantial mitigation effort of 47 dB is required as can be read from this figure.

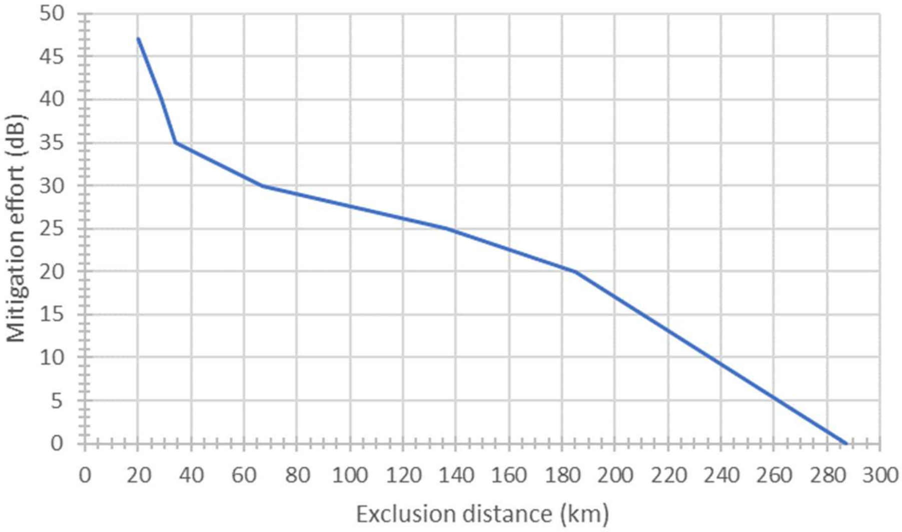

Figure 3.2: Mitigation effort versus exclusion distance (for both dishes combined).

In the figure above, the protection requirements of both dishes have been combined. In the figure below, the results for both dishes (the one pointed at Alphasat and the one pointed at Inmarsat-4F2) are shown separately.

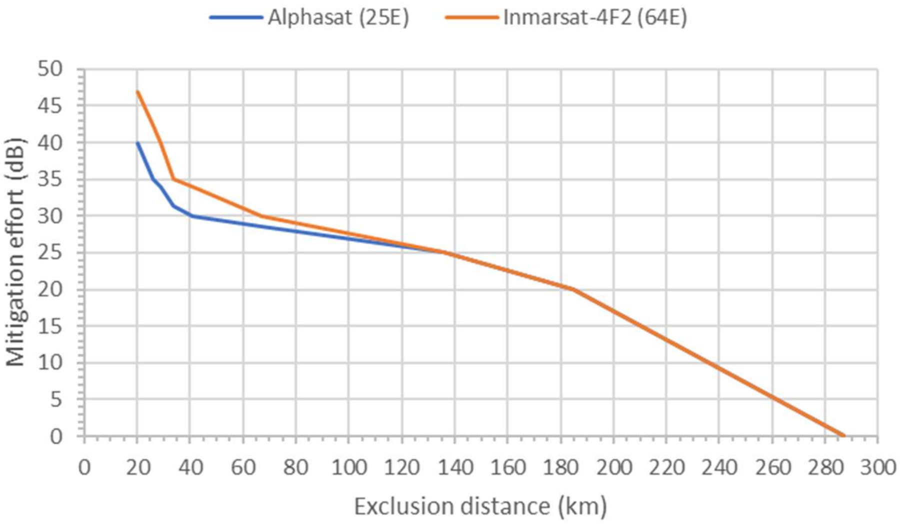

Figure 3.3: Mitigation effort versus exclusion distance.

As can be noted, protection of the dish pointed at Inmarsat-4F2 is dominating the results (i.e. requires the most mitigation effort for a given exclusion distance). This is due to the fact that the antenna pointing to Inmarsat-4F2 is operating at the lowest elevation angle of 10^0, which results in a higher antenna gain (compare Figures 3.5 and 3.7), while its azimuth of 116.8^0 is in the direction of the city Groningen (see Figure 3.4) which is nearby at a distance of 20~30 km. The antenna pointing to Alphasat operated at a higher elevation angle (26.7^0) and an azimuth of 157^0 and the nearest city in this direction is Assen at a larger distance of 35~45 km (see Figure 3.6).

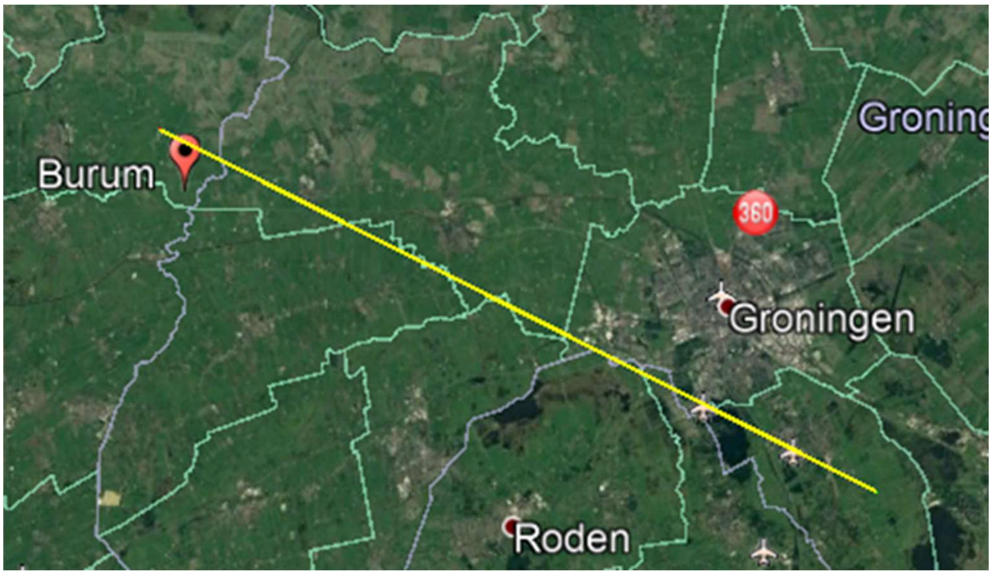

Figure 3.4: Antenna azimuth pointing towards Inmarsat-4F2 (elevation of 10^0).

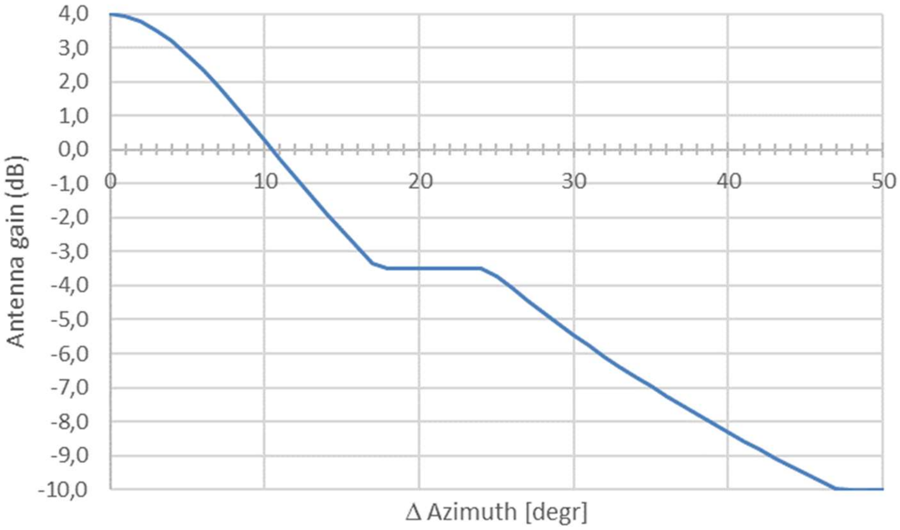

Figure 3.5: Antenna gain as function of the azimuth (with respect to main azimuth direction of 116.8^0) for dish pointing at Inmarsat-4F2.

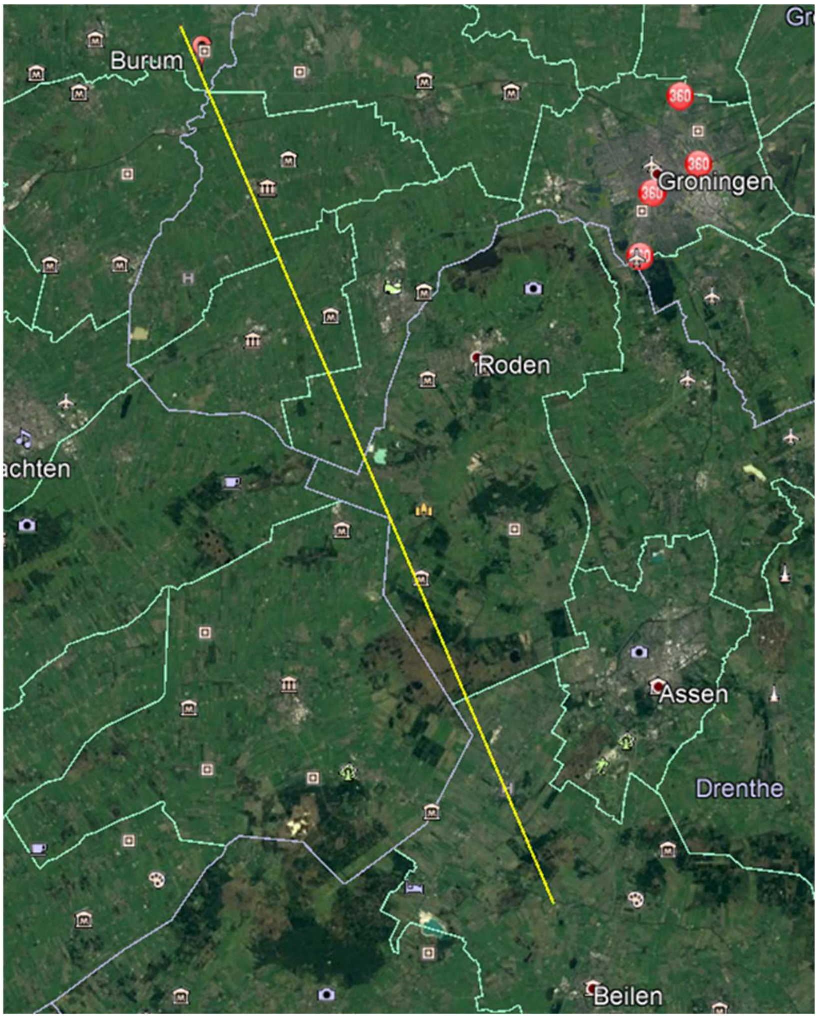

Figure 3.6: Antenna azimuth pointing towards Alphasat (elevation of 26.7^0).

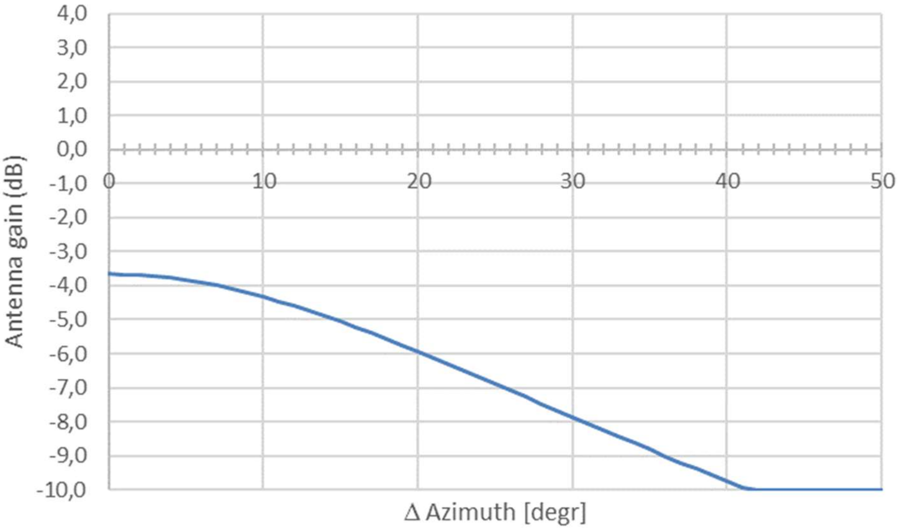

Figure 3.7: Antenna gain as function of the azimuth (with respect to main azimuth direction of 157^0) for dish pointing at Alphasat.

Looking at the municipalities which are dominating the results for various mitigation effort and exclusion distance combinations shown in Figure 3.8 and 3.9, the following is observed.

With 47 dB mitigation effort, the exclusion distance of 20 km is almost totally determined by Groningen (for 99.5%).

With 40 dB mitigation effort, the exclusion distance of 29 km is mainly determined by Haren (for 95.6%).

With 35 dB mitigation effort, the exclusion distance of 34 km is mainly determined by Veendam (72.1%), Stadskanaal (13.2%), Tynaarlo (5.0%) and Assen (4.6%).

With 30 dB mitigation effort, the exclusion distance of 67 km is mainly determined by Emmen (83.3%) and Vlagtwedde (14.3%).

Note that all these municipalities are on or near the azimuth line of the SAS Burum dish aimed at Inmarsat-4F2 and also close to the edge of the exclusion zone (see Figure 3.9).

At larger exclusion distances, the exclusion zone passes the border with Germany (as shown in Figure 3.8) and there are no longer Dutch municipalities present near the azimuth line outside the exclusion zone. It should be noted that 5G deployment outside The Netherlands is not taken into account in this study. If, however, the 5G deployment in Germany would be similar to the one in the Netherlands, one might expect the interference originating from German 5G networks in the azimuthal pointing angles of Burum SAS to become dominating at exclusion distances exceeding 70 km. As shown in Figure 3.2, this would require a mitigation effort of about 30 dB (being also applicable to 5G networks in Germany).

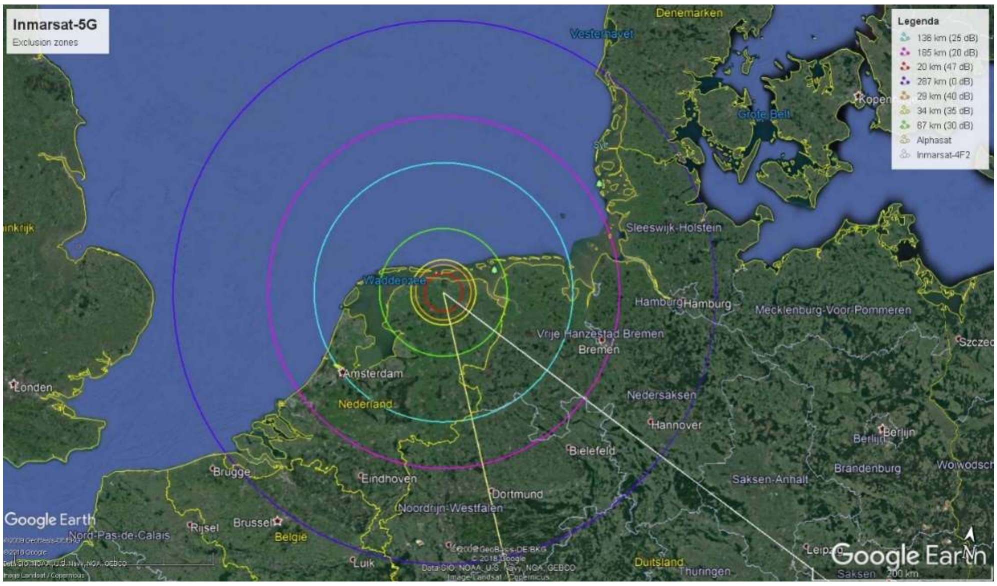

Figure 3.8: Exclusion zone examples.

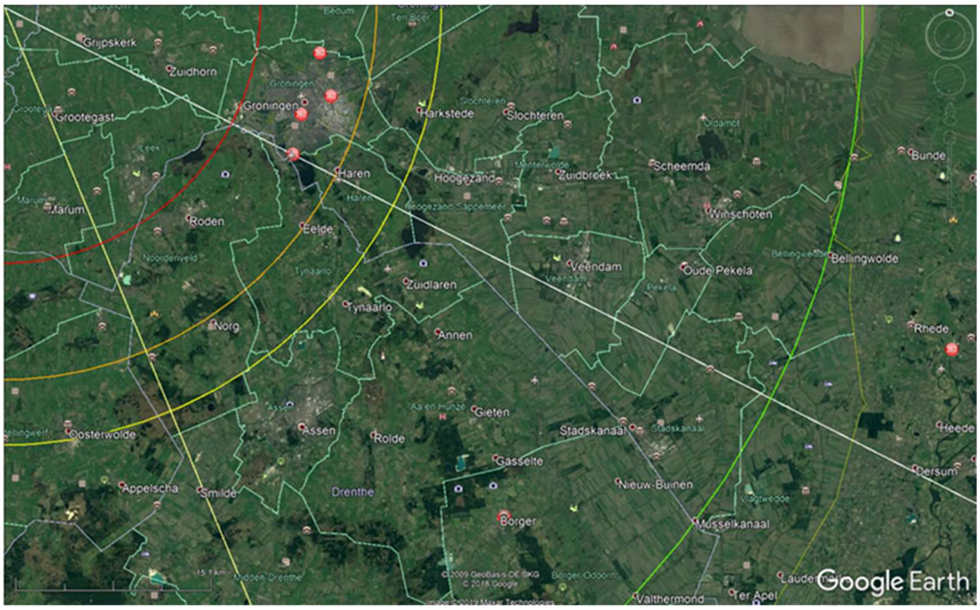

Figure 3.9: Exclusion zone examples (zoomed in, green lines indicating municipalities).

At the larger exclusion distances, the following dominating municipalities are found.

With 25 dB mitigation effort, the exclusion distance of 136 km is mainly determined by Amsterdam (47.8%) and Haarlemmermeer (38.8%).

With 20 dB of mitigation effort, the exclusion distance of 185 km is mainly determined by Rotterdam (61.7%) and The Hague (36.2%).

With 0 dB of mitigation effort, the exclusion distance of 287 km is totally determined by the only remaining municipality Sluis.

The exclusion zone for a given mitigation effort is found to be mainly determined by the large (densely populated) municipalities near the edge of the exclusion zone. At these larger exclusion distances, the interference arrives at the dishes in Burum SAS at off-axis angles for which both antenna gains are almost the same, which is the reason that in Figure 3.3 the curves of both dishes coincide for large exclusion distances.

3.4 Summary

5G mobile networks operating in the frequency bands 3450-3550 MHz and 3676-3750 MHz (i.e. outside the Burum SAS operating frequency band of 3550-3676 MHz) can be employed nation-wide, except within an exclusion distance of 21 km (from Burum SAS). This exclusion distance can be reduced further by taking some mitigation effort, like applying filtering at Burum SAS to avoid blocking (i.e. attenuating the 5G interference received in adjacent channels, before they reach the LNA, as discussed in the next chapter).

5G mobile networks operating in the same frequency band as used by Burum SAS (3550-3676 MHz) will require a significant mitigation effort to obtain similar exclusion distances (47 dB for 20 km).

In this case, the required mitigation effort to obtain a given exclusion distance is determined by:
- the short term criterion;
- the protection requirements of the dish pointing at Inmarsat-4F2

In addition, it is largely determined by the municipalities near its azimuthal direction and/or near the edge of the exclusion zone.

Noting that municipalities near the azimuthal direction of Inmarsat-4F2 and/or near the edge of the exclusion zone are largely determining the mitigation effort / exclusion zone curve, mitigation measures (at 5G side) would be most effective when applied in these municipalities.

Noting these sensitive directions, and with a similar 5G deployment in Germany as in the Netherlands, the interference from 5G networks in Germany can be expected to become the dominating factor determining the interference at Burum SAS at exclusion distances exceeding 70 km. To cope with this a mitigation effort of about 30 dB is required, which is also applicable for 5G networks in Germany[9]. This also means that mitigation efforts below 30 dB (or exclusion distances exceeding 70 km) are not very useful to consider without taking the interference originating from 5G networks in Germany into account[10].

At last, the situation for Burum SAS is compared with the one for the Burum Interception Facility at a production loss of 0.0038% (requirement) and 1% using the same scenario S3e. As shown in the figure below, the mitigation effort for Burum SAS is up to 18 dB below that of the Burum Interception Facility at a production loss of (0.0038%) and close to the one at a production loss of 1%.

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[9] Assuming the 30 dB mitigation effort is equally split between the Burum SAS and 5G mobile networks, this means that both the German as well as the Dutch networks have to take mitigation measures to obtain a suppression of 15 dB.

[10] Note that only the interference originating from 5G networks in The Netherlands have been taken into account.

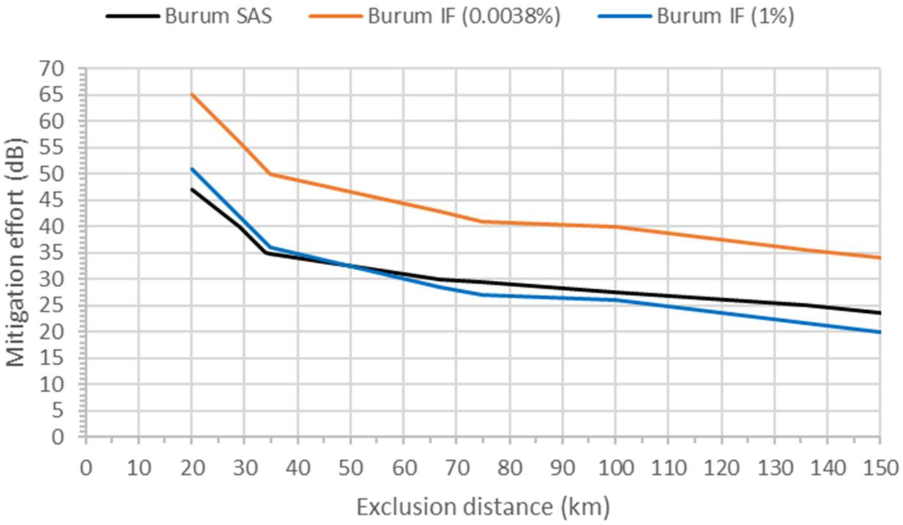

Figure 3.10: Burum SAS compared to Burum Interception Facility.

4 Mitigation measures

4.1 Adjacent channel interference mitigation measures

In general all co-channel interference mitigation measures (discussed in the next section) can also be applied as adjacent channel interference mitigation measures.

One specific measure which is very effective in case of adjacent channel interference (only) is the application of a filter before the LNA's at the dishes of Burum SAS. Attenuation of the interference in adjacent channels of 30 dB or more can be achieved (see example in the figure below[11]) which enables the exclusion distance to be substantially reduced.

The filter will also significantly attenuate the interference produced by local 5G deployments (discussed in Chapter 3).

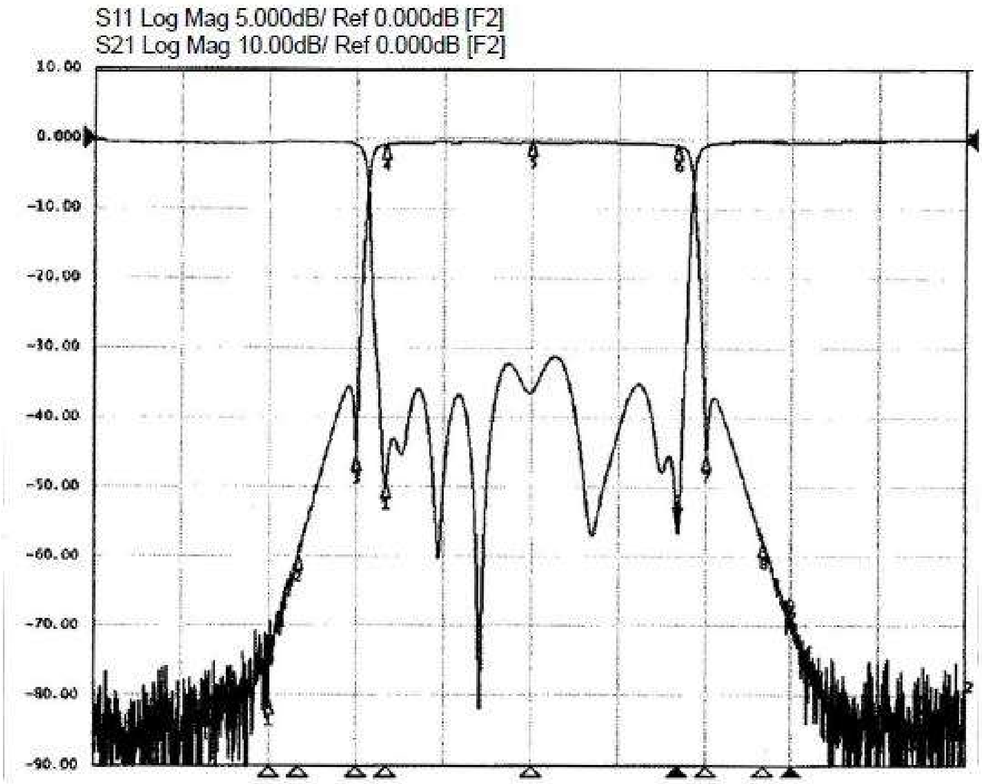

Figure 4.1: Filter example (MFC 13961W)[12]

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[11] This example is not tailored to our case, but is included to show what could be achieved.
[12] https://www.vsatplus.com/collections/rf-filter/products/mfc-13961w-c-band-interference-elimination-filter?variant=33582206029

Table 4.1: Values as indicated by the markers in the figure above

Marker (left to right)	Frequency (GHz)	Attenuation (dB)
1	3.50	80.58
2	3.55	59.77
3	3.65	45.59
4	3.70	0.80
5	3.95	0.45
6	4.20	0.87
7	4.25	45.42
8	4.35	57.93
9	4.40	70.08

At the small distances the exact locations of the nearest 5G base stations are however important for the obtained result and have to be taken into account in more detail when the actual 5G base stations are rolled out (the tool that we use for the calculations only considers one particular situation, which may not be the actual future one). This is because at close distance 5G antennas can be nearer to the main beam of the satellite dish (i.e. the interference can arrive at the dish at much smaller of axis angles then for 5G stations at long distance) .

Besides a high attenuation of signals in the adjacent channels, it is also important for this filter to have a very low attenuation in the frequency band of operation (3550-3676 MHz)[13].

Available filters, like the one in our example, are about 500 US$. It may however prove to be difficult to find one that is tailored to the operational frequency band of Burum SAS (3550-3676 MHz). In this case, a specific filter can be designed for it, but this will increase cost. As an alternative an existing filter might be used having a close, but not perfect, fit that would still filter out most of the interference (in case there is no need to reduce the exclusion distance to the absolute minimum that could be obtained with a tailored filter).

4.2 Co-channel interference mitigation measures

Mitigation measures can be considered to be applied to 5G networks as well as to Burum SAS. They have been discussed in detail in reference [1].

4.2.1 Mitigation measures which can be taken in 5G networks

The mitigation measures which can be taken in 5G networks will reduce the RF levels of the signals (originating from 5G networks) that arrive at Burum from various angles.

The mitigation measures are summarized below and for a detailed discussion of each mitigation measure we refer to section 5.4.4 of [1].

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[13] Note that an attenuation of 0.4 dB will already have the same impact on the signal-to-noise ratio of the received satellite signals as the maximum permissible (long term) interference.

Table 4.2: Mitigation measures which can be taken in 5G networks

Mitigation measure	Effectiveness
1. Exclusion zone/distance Circular area, with Burum SAS as centre and radius equal to the exclusion zone, within which 5G base stations are not allowed to transmit in the operational frequency band (3550-3676 MHz) of Burum SAS.	Up to 17 dB for exclusion zone from 20 to 70 km (see Figure 3.10)
2. Reduction in transmission power	Combination: up to 20 dB Massive MIMO: 3 to 11 dB
3. Antenna related measures (conventional) a) Increasing antenna tilt b) Sector antenna removal	
4. Antenna related measures (adaptive antennas) a) Increasing antenna tilt b) Creating a null in the antenna diagram c) Sector non-illumination	
5. Antenna height reduction (in urban areas to take advantage of shielding by buildings)	
6. Small cells (hot spots/zones)	
7. Traffic related measures (offloading to small cells, unlicensed spectrum (5 GHz) or to higher frequencies such as the 26 GHz band)	Almost none

4.2.1.1 *Exclusion zone/distance*

As a mitigation measure, an exclusion zone is simple to implement. The effectiveness of an exclusion zone is especially high for exclusion distances up to 35 km. Beyond 35 km, the mitigation effort only drops slowly with increasing exclusion distance (see Figure 3.10; based on short term criterion). This drop would even be more slowly, when the interference from 5G networks in Germany would have been taken into account. The introduction of an exclusion zone goes against the concept of a nation-wide mobile network. The business impact also becomes substantial when the exclusion zone occupies a substantial part of the country (e.g. size of a province or more). Such a large gap in the 5G service area, can be quite problematic for a national operator.

4.2.1.2 *Transmit power, antenna and antenna height related measures*

Note that scenario S3e (nationwide, capacity, evolved; late stage) as described in [1] has been selected for this study. This scenario is based on nationwide coverage and a certain capacity being provided. Some of the mitigation measures mentioned in the Table above may however affect the coverage and/or capacity of a cell and hence result in coverage/capacity gaps affecting the scenario. To remain the same scenario, these gaps have to be compensated for. This can for instance be achieved by cell densification. Such a compensation measure will however increase the interference originating from the 5G network, which will reduce/limit the effective mitigation effort that can be obtained by the mitigation measure. The mitigation measures for which compensation measures have to be taken into account are mitigation measures 2, 3, 4 and 5 mentioned in the Table above.

Applying cell densification to compensate coverage/capacity gaps also has the disadvantage of increasing cost (CAPEX and OPEX) for the MNO. For any combination of mitigation measures 2-5, the applied cell densification to compensate for coverage/ capacity gaps should therefore be limited. Instead of cell densification, other options to compensate for coverage / capacity gaps are worthwhile to consider.

As a simple example, sector antenna removal is considered to illustrate the aforementioned disadvantage. In general, a mobile network could use a hexagonal cell structure with three sector antennas per cell (as shown left in the figure below). Removing a sector antenna in each cell, an alternative cell structure can be created as shown on the right in the figure below. Assuming the removed sector antennas were pointing in the direction of Burum, this could reduce the transmitted power in the direction of Burum by about 20 dB (depending on the actual radiation pattern of the sector antenna used). While the coverage and capacity in each sector remains the same, 1.5 times more cells are required to keep continuous coverage. This compensation measure will increase the transmitted power in the direction of Burum by 1.8 dB. The net result of the mitigation (including the compensation) measure would then be 18.2 dB. This result is achieved at the cost of a 50% increase in the number of cells.

Instead of cell densification, the transmit power could also be increased to remain an equal cell size. This would reduce the net result of the mitigation measure to around 16.5~17.5 dB[14], but is less costly. The limitation in the mobile terminal transmit power will place an upper limit to this power increase at the base station side.

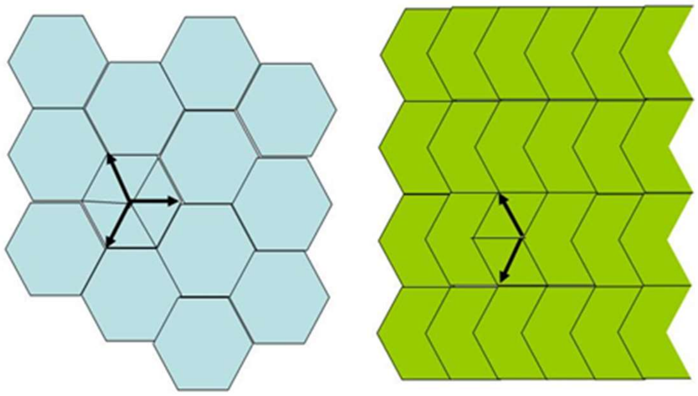

Figure 4.2: Sector antenna removal

The effectiveness of these mitigation measures can be high and on itself the various mitigation measures are also feasible. The business impact does however increase rapidly when high mitigation efforts are to be achieved (15~20 dB). The necessary compensation measures, like cell densification (see also next section), will then start to significantly increase cost or, in case of other compensation measures, will limit the ways in which the cell coverage/capacity can be tailored to local needs and environment.

Compared to conventional antennas, adaptive antennas allow the same to be achieved in a more flexible way and with less impact on coverage/capacity. Instead of for instance removing a sector antenna they allow a null to be created in the

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[14] Due to the path loss exponent exceeding 2 in most environments (3-4).

direction of Burum with a smaller coverage/capacity gap which requires less compensation.

Adaptive antennas (like massive MIMO) also have an inherent mitigation effect because the average transmitted power in the direction of Burum is much less compared to a conventional antenna. Monte Carlo simulations conducted by TNO with urban and suburban deployment models indicate that an additional 3 to 11 dB can be gained compared to a conventional sector antenna in the same situation [1].

4.2.1.3 *Small cells*

Small cells (mitigation measure 6) can be taken as an example of combining multiple mitigation measures. Small cells can be characterized by a low transmission power, omni-directional antenna and a lower height above street level compared to sites of the macro network. In an urban area, they can also take advantage of the shielding effect provided by surrounding buildings. To get a coarse estimate of the net effect, the macro network in a PC-4 downtown area in Groningen has been replaced by a small cells grid (ISD of 200 m instead of 500 m in case of the macro network) in [1]. This led to a reduction of approximately 20 dB of signal energy that escaped from this area, at the cost of a six time increase in the number of sites which represents a serious business impact.

Small cells will be less effective in rural areas where hardly any effective shielding objects are present.

4.2.1.4 *Traffic related measures*

An intentional traffic load reduction can be achieved with offloading techniques. The technology of traffic offloading mechanisms is mature and traffic offloading techniques in 5G will be part of the (automated) network management tools.
The business impact of intentional traffic offloading would be an ordinary one if it is done to maintain targeted network performance levels and avoid congestion.
The 3.5 GHz band is however considered by operators as an important band to offload to, which will limit the effectiveness of this measure. To be effective as a mitigation measure, offloading would have to be done to higher bands (licensed or unlicensed), or small cells (outdoor and indoor) in the 3.5 GHz band (network densification).

4.2.2 *Mitigation measures which can be taken at Burum SAS*

The mitigation measures which can be taken by SAS Burum are basically the same as those mentioned for the Burum Interception Facility in section 5.5.4 of [1].

Some of the mitigation measures which can be taken at SAS Burum, as well as their effectiveness, will differ from those for the Interception Facility due to technical and operational differences as well as the different protection criteria. These differences are indicated below. For a detailed discussion of each mitigation measure we refer to section 5.5.4 of [1].

Table 4.3: Mitigation measures which can be taken at Burum SAS

Mitigation measure	Effectiveness
1. Acceptance of lower availability (of Inmarsat services) Similar to the acceptance of a higher production loss by the Burum Interception Facility.	3~5 dB at unavailability 0.1% 7.5~9.5 dB at unavailability 1%
2. RF Shielding (RF Screen)	up to 10 dB
3. Conventional satellite dish adjustments a) Dish reflector edge treatment b) Dish diameter increase c) Multiple feeders (e.g. side lobe suppression) d) Offset reflector	up to 9 dB
4. Advanced antenna solutions a) Phased Array Feeder (side lobe suppression, nulling) b) Alternative interception concept (not applicable to Burum SAS)	Nulling: - small: 30~40 dB - wide: less
5. Signal processing techniques (spatial filtering)	To be proven
6. Notch filtering (of SSB burst) Impact can only be determined if more details are known (like frequency location of SSB which depends on the spectrum obtained by the MNO).	To be determined, but only partial solution

4.2.2.1 *Acceptance of lower availability (of Inmarsat services)*

From a technical point of view the acceptance of a lower availability is a mitigation measure in its own right, but may conflict with existing service level agreements with users of the various Inmarsat services. The business impact could be quite substantial.

To have an indication what can be achieved by the acceptance of a lower availability, the mitigation effort as function of the exclusion distance is shown in the figure below for an unavailability of 0.005% (standard short term criterion, blue line), 0.1% (green line) and 1% of the time (orange line).

Compared to the 0.005% unavailability standard curve the acceptance of an unavailability of 0.1% would reduce the mitigation effort by 3~5 dB, while the acceptance of an unavailability of 1% would reduce the mitigation effort by 7.5~9.5 dB.

Also included is the curve considering the long-term criterion only (i.e. neglecting the short-term criterion, red line). At any point below the long-term curve (red line) the long-term criterion is not met. Since the long-term criterion represents a more broader/general criterion, which is also applicable for other (non-satellite) systems, this curve is considered to be a hard lower limit. This means that when both the short- and long-term criteria have to be met, the highest mitigation effort of both curves is applicable.

Feasibility of this mitigation measure is obvious and its effectiveness depends on the acceptable unavailability, which has be determined by Burum SAS based on its business impact.

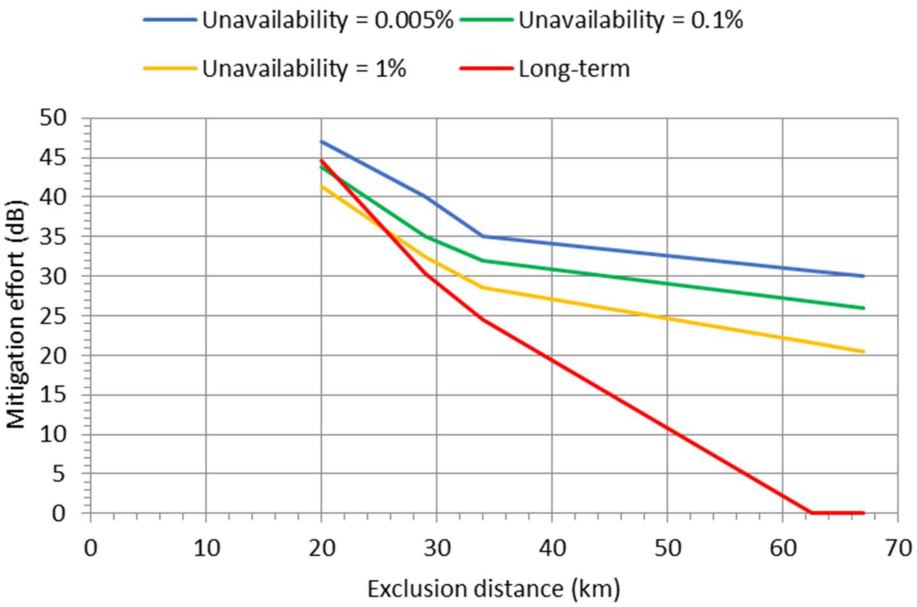

Figure 4.3: Short-term versus long-term criterion.

4.2.2.2 *RF shielding*

Reducing the interference by the use of shields has been investigated by TNO for the co-located interception facility [2]. Although shielding can very well be applied to locations with only a single satellite dish, the situation is much more complicated in Burum where multiple satellite dishes are co-located.

On one hand, to provide any attenuation of interference, an RF screen has to be at least higher than the top of the Burum SAS dishes (16.5+ meters) and sufficiently wide. On the other hand, the maximum height of the screen is restricted by the fact that each surrounding dish has to be able to “see” the satellite of which it has to receive the signals (clearance issue).

Due to this complexity, all the unknown factors (like the exact positions of all dishes and the satellites each dish has to be able to “see”) and the considerable amount of time needed to investigate the possibilities of screening, no reliable indication of what can be achieved can be provided. Based on the insights from our previous study [2], it is however expected that the protection that can be achieved by shielding will be limited.

A detailed study might prove the placement of a screen of sufficient width and height to be possible in the area South-East of Burum SAS. Such a screen could provide attenuation of signals arriving from 5G base stations near the azimuthal directions of the dishes (see Figures 2.2 and 3.8). Interference originating from these directions is shown to be dominant for exclusion distances less than about 70 km (see Chapter 3). If proven to be a viable solution, such a screen might achieve sufficient attenuation to be considered as mitigation measure. At exclusion distances beyond 70 km, the main interference from 5G networks deployed in The Netherlands is coming from other directions (see Chapter 3) in which case the contribution of the shield to the mitigation effort will reduce to zero. Only for interference originating from Germany, it may then still prove to be a useful mitigation measure.

Some other mitigation measures, like the use of larger dishes discussed in the next section, may require new locations of the dishes for the satellite services to remain operational. Depending on the new locations, this may either open up new possibilities or further limit the possibilities of the placement of an RF screen as well as its required minimum height.

The feasibility of an RF screen is subject to some fundamental phenomena, but is foremostly an engineering challenge. There is also an environmental impact to be taken into consideration because of the heights involved. If a screen of sufficient height and width can be placed it *could* reduce the interference by 10 dB, but performance predictability of an RF screen with a given design is not very good due to all factors involved in this case. The business impact concerns a possible (future) expansion of Burum SAS, since a screen will limit the possible locations available for new dishes (due to the clearance issue). In addition, safety issues concerning personal placing the screen may require the dishes to cease transmissions for some period(s) of time which affect the satellite services provided.

4.2.2.3 Dish adjustments

Antenna (dish) improvements can be made to achieve a higher maximum gain, which will increase the received satellite signal levels such that they can withstand higher interference levels. Also a reduced gain in the direction(s) of the main interference sources can be achieved, which reduces the total received interference.

Both improvements can for instance be achieved by using larger dishes, providing higher maximum gains and improved radiation patterns. To determine how much this can contribute to the mitigation effort, a small internet search has been performed for available large C-band dishes. Although very large dishes with diameters up to 30 m are known to have been used in the past (and may still be operational), the satellite capabilities have been evolved in such a way (having higher output powers and using spotbeams) that smaller (cheaper) dishes are used nowadays. The largest dishes found have diameters around 16 m. One dish with a diameter of 20 m was however also found[15]. This dish is commercial available and therefore a realistic viable option to replace the current 13.1 m dishes used at Burum SAS and it is of interest to see what can be gained by it.

One aspect of the larger 20 m dish is the higher maximum antenna gain of 56 dBi (@ 3.625 GHz, [1]) compared to the 52.5 dBi (@3.625 GHz) of the current 13.1 m dish. This 3.5 dB higher maximum gain will be considered purely as a mitigation measure. This means that it is used to relax the permissible interference levels of the protection criteria and not to improve the performance and/or availability of the satcom system.

Concerning the long term criteria, the increase in maximum antenna gain will increase the received satellite signal levels by the same amount. To remain the same signal-to-noise ratio, this allows the noise level to be increased also. This

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[15] https://www.antesky.com/project/20m-earth-station-antenna/

means that the total permissible (long term) interference level can be increased by almost 11 dB without affecting signal quality, from -10 dB below the noise level (original required maximum permissible interference of 10%) to 0.93 dB above the noise level ($10\log(10^{0.35}-1)$).

Concerning the short term criteria, the increase in maximum gain can be regarded as in increase of the fading margin M_S. According to SF.1006, the permissible interference level is depending om the fading margin M_S by the factor $10\log(10^{Ms/10}-1)$. Increasing the fading margin M_S from 2 dB to 5.5 dB will therefore allow the permissible (short term) interference level to be increased by 6.4 dB without an additional availability reduction.

Besides the relaxed criteria, the improved antenna diagram of the larger dish will also have a positive effect.

The results of the calculations with the relaxed criteria for the 20 m dish are shown in the figure below. Both the curves for the current 13.1 m dish and the larger 20 m dish are determined by the short term criterion only. Compared to the current 13.1 m dish, the larger 20 m dish requires up to 9 dB less mitigation effort for a given exclusion distance.

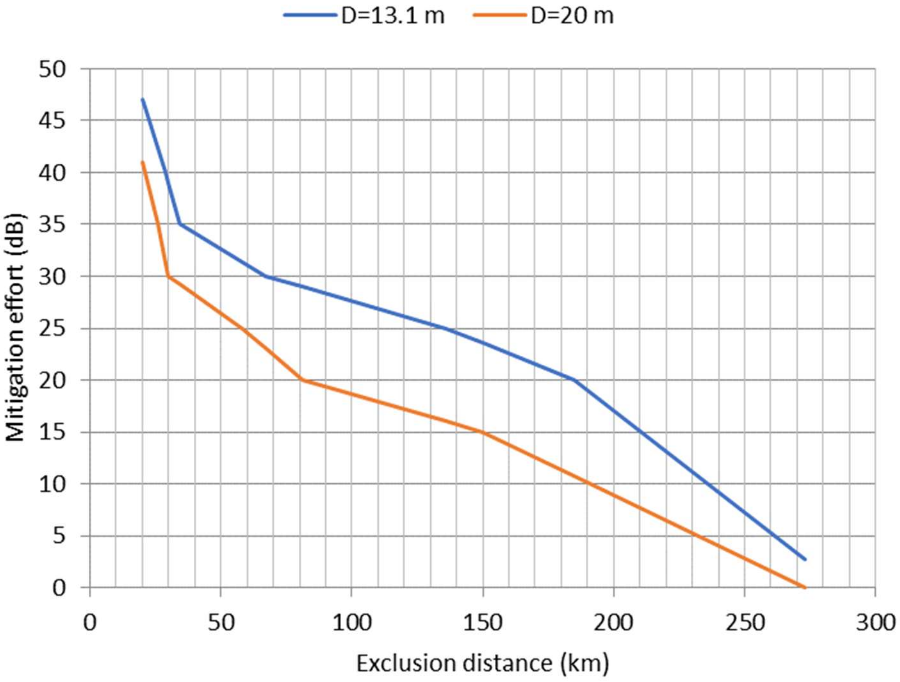

Figure 4.4: Effect of increasing the dish diameter from 13.1 to 20 m.

The disadvantage of a larger dish is the (one time) cost. An old rule of thumb says that the cost are proportional with $D^{2.5}$, D being the diameter of the dish. So, compared to a 13.1 m dish, the 20 m dish will be $(20/13.1)^{2.5}$ = 2.9 times more expensive.

Furthermore, new locations for these dishes may have to be found, when the current dishes have to remain operational in order not to affect the satellite services.

As a mitigation measure it is feasible (larger dishes have been present) and quite effective. Larger dishes may however introduce some clearance issues, which can have a future business impact (limiting the possible locations available for new dishes).

Other adjustments applied to current dishes will also have a (temporary) business impact, since they cannot be used for transmissions (for safety reasons) during the periods that personnel are working on the dishes.

4.2.2.4 *Advances antenna solutions*

Phased Array Feeders can bring substantial effectiveness in case of nulling (in the order of 30-40 dB), but this is complex and expensive technology requiring a major engineering effort. The diffuse nature of the aggregated interference coming from multiple base stations may require a rather broad ‘’null’ to be created which may reduce the effectiveness which can be achieved.

4.2.2.5 *Signal processing techniques (spatial filtering)*

This is a more a conceptual mitigation measure, mentioned for completeness. Whether it is viable option in our case remains to be proven, considering the diffuse nature of the aggregated interference coming from multiple base stations and the low spatial separation (for at least the dish pointing at Inmarsat 4F2).

4.3 Summary

4.3.1 *Mitigation measures in 5G networks*

An increased exclusion zone is very effective in lowering the mitigation effort especially at smaller exclusion distances (up to 35 km). Mitigation measures concerning transmit power, antenna (diagrams) and antenna height or a combination (like small cells) can be also be very effective. Their business impact does however increase rapidly when high mitigation efforts are to be achieved (15~20 dB). The necessary compensation measures, like cell densification, will then start to significantly increase cost. In case other compensation measures are used, they will limit the ways in which the cell coverage/capacity can be tailored to local needs and environment or limit the net effectiveness of the mitigation measure.

4.3.2 *Mitigation measures at Burum SAS*

Accepting a reduced link availability contributes to mitigation but may conflict with SLA’s in place. It is up to Inmarsat decide whether and to which extent they would agree to such a measure. The contribution of an RF screen to the mitigation effort can be significant, but we question the practicality of this solution for Burum SAS. The most promising mitigation measures concern the dishes, of which for example the use of a larger (20 m) dish is representing an existing (low risk and development) option able to already provide a significant 7~9 dB of mitigation effort.

5 Final analysis and conclusion

5.1 Summarized findings on co-existence and applicable mitigation effort

Co-existence calculations have been conducted based on the existing Inmarsat configuration, the most developed national 5G network deployment scenario and applicable ITU protection criteria for satellite communications.

5G mobile networks operating outside the Burum SAS operating frequency band of 3550-3676 MHz (in the frequency bands 3450-3550 MHz and 3676-3750 MHz) can be employed nation-wide, except for an exclusion zone (within 21 km from Burum SAS). This exclusion distance can be reduced substantially by taking some mitigation effort, like applying filtering at Burum SAS to avoid blocking (i.e. attenuating the 5G interference received in adjacent channels, before they reach the LNA).

5G mobile networks operating in the same frequency band as used by Burum SAS (3550-3676 MHz) will require a significant mitigation effort to obtain similar exclusion distances (47 dB to reach a 20 km remaining exclusion zone[16]). The minimum mitigation effort reduces as the exclusion zone is chosen larger. Beyond the 70 km range, the contribution from 5G networks in Germany can no longer be ignored and even could become the dominating factor.

The required mitigation effort to obtain a given exclusion distance is found to be determined by the short term criterion and the protection requirements of the dish pointing at Inmarsat-4F2. Moreover, the mitigation effort is largely determined by the municipalities near its azimuthal direction and/or near the edge of the exclusion zone. Beyond a range of 120 km, the protection requirements for both terminals become alike, so similar coexistence conditions with 5G networks apply.

5.2 Summarized findings on mitigation possibilities

Mitigation measures both on 5G side as well as Inmarsat side have been discussed.

With respect to mitigation possibilities on the 5G network side, various infrastructure related measures can be applied which indeed have a suppressing effect upon radiation levels in the direction of Burum. The practical effectiveness of these measures depend on network deployment characteristics and are also situation dependent. As we motivated in [1], a mitigation result in the order of 20 dB through a certain combination of measures is technically feasible with existing short-term solutions but they have an impact on the roll out strategy and the operator’s business case. Higher mitigation targets on mobile networks become progressively difficult to achieve because not every measure can be applied everywhere and proposed measures are not mutually independent. Traffic related measures have also been mentioned but neglect the very reason for operators to get into the 3.5 GHz band, i.e. to be able to offload current traffic to that new band.

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[16] Compare this with [1] where with 46 dB mitigation resulted in an exclusion zone of 50 km.

As noted above, the municipalities near the azimuthal direction of Inmarsat-4F2 and/or near the edge of the exclusion zone are largely determining the mitigation effort / exclusion zone curve. This means that 5G related mitigation measures would be most effective when applied in these municipalities[17].

On the Inmarsat side, there are various options to consider (in arbitrary order) which are mainly applicable to the terminal pointing at Inmarsat-4F2. The service availability could be considered as a mitigation measure. We have seen that the protection against short term interference according to ITU recommendations requires a substantial mitigation effort. Whether this can be relaxed, depends entirely on Inmarsat and the margin they have in the service level agreements with their customers. Enlargement of the dish is a well understood measure with a reasonable effectiveness (9 dB) but will require rebuilding the corresponding platforms. The use of other feeders is a second direction of solutions, at the price of some loss in link margin. Conventional feeder adjustment may deliver up to 10 dB in theory, but practical engineering should indicate what is achievable with an actual system. Phased Array Feeders can bring substantial effectiveness (in the order of 30-40 dB) but this is complex and expensive technology requiring a major engineering effort. The RF screen solution has been inspected, leveraging the extensive work we did in 2016. A suppression in the order of 10 dB is a realistic design goal but the entire dish constellation at Burum needs to be taken into account in any screening solution (practical challenge), and it’s actual suppression effectiveness cannot be well proven in advance due to propagation related phenomena. Advanced antenna techniques have not been looked into due the large portion of research associated with such types of solutions. As in the case of 5G networks, separate mitigation measures cannot be simply added as for example the enlargement of a dish does affect the useful room for mitigation that is left to be accomplished with PAF. Also enlargement of the dish has implications for a screen solution. All matters considered, our professional estimation is that a mitigation result in the order of 10-15 dB could be achieved with technologically mature solutions. Targeting higher gains will quickly become more complex, more costly and requires a longer development and implementation time.

5.3 Final discussion and conclusion

Cochannel co-existence is the main problem as adjacent channel interference reaches tolerable levels when 5G networks stay outside a 20 km exclusion zone, which could also be further reduced with relatively modest measures. To make the cochannel interference issue compatible with the adjacent channel situation, a mitigation effort of at least 46 dB is required if the ITU protection criteria are obeyed, recognizing the short term criterion is most critical. The existence of 5G networks in Germany creates a future interference floor which has not been well quantified, but our current analysis shows that effectively mitigating the interference contribution on Dutch soil starts at approximately 30 dB suppression. It is important to realize that in the long run (towards 2030) the interference pressure coming from 5G networks (NL and Germany) may well increase beyond what is predicted with our “most developed deployment” scenario that has been used in our calculations. Additionally, the level of realism of this NL-scenario has been an important factor in

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[17] A higher mitigation effort in the dominating municipalities (relative small area) would allow for a lower mitigation effort in the remaining of the Netherlands (much larger area).

its design. Power levels applied in our scenario do not fully exploit the room the licence would provide operators, based on EC Decision 2014/276/EU[18].

It is not up to TNO to determine how the mitigation burden must be shared. In the investigations for the Burum Interception case, we assumed a 50% share between both applications. If this is also applied in this case we are looking at 23 dB minimum suppression targets on the 5G networks and on the Satcom side, at least for the short to mid-term situation (being the validity period of our 5G deployment scenario). Analysis has indicated that such mitigation gains are not impossible but already technically demanding and will have specific business impacts on each side. It does however make sense to first look at what is actually achievable on short and mid-term at the satcom side, as these measures are effective towards any 5G network (either Dutch or German). The remaining mitigation effort would obviously have to come from the mobile networks' side with a certain exclusion zone as the closing measure.

Below we summarized our findings on mitigation on which we based our opinion regarding the feasibility of a co-channel co-existence arrangement. Effectiveness relates to the contribution of the particular measure to the overall mitigation target. The business impact is to be interpreted as the structural rather than the incidental business impact due to one time costs of the implementation of a measure.

SAS measure	Effectiveness	TRL	Business impact
Lower service availability	Moderate	High	High
RF shielding	Moderate, low predictability	Moderate	Possibly
Satellite dish adjustments	Moderate	High	Neutral
Advanced antenna solutions	High	Low	Neutral
Signal processing	Unclear	Low	Neutral
Notch filtering	Moderate	High	Possibly

5G measure	Effectiveness	Maturity	Business impact
Exclusion zone	Moderate (within 50 km)	High	High
Conventional EIRP reduction measures	Moderate	High	High
Advanced antenna techniques	High, low predictability	Low	High
Traffic related measures	Low	High	Moderate

Hence, given the mitigation target as described, the conclusion is that, based on our assessment of possible mitigation measures on both sides in terms of

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[18] Source: EC, *Commission Implementing Decision on amending Decision 2008/411/EC on the harmonization of the 3 400-3 800 MHz frequency band for terrestrial systems capable of providing electronic communications services in the Community*, 2014/276/EU, 2 May 2014.

effectiveness, technological readiness and business impact, we are pessimistic about the practical achievability of a co-existence arrangement between these applications.

6 Abbreviations

AR	Antenna Register
BGAN	Broadband Global Area Network
CEPT	European Conference of Postal and Telecommunications Administrations
DL	Downlink
EC	European Commission
EU	European Union
EZK	Ministry of Economic Affairs and Climate Policy (Dutch: Economische Zaken en Klimaat)
ICAO	International Civil Aeronautical Organization
ITU	International Telecommunications Union
IMO	International Maritime Organisation
ISD	Inter-Site Distance
LNA	Low Noise Amplifier
mMIMO	massive MIMO
MIMO	Multiple Input Multiple Output (antenna)
MNO	Mobile Network Operator
NL	Netherlands
NR	New Radio
PAF	Phased Array Feeder
PC-4	Postcode-4 level area
RAN	Radio Access Network
RF	Radio Frequency
SAS	Satellite Access Station
SPS	Satellite Phone Services
SSB	Signal Synchronisation Block
TT&C	Telemetry, Tracking, and Command
TRL	Technology Readiness Level
UL	Uplink
URLLC	Ultra Reliable Low Latency Communications

7 Literature

[1] *Co-existence of 5G mobile networks with C-band Satellite Interception Burum*, A.H van den Ende, H.J. Dekker, report TNO 2018 R11156, November 2018,

[2] *Investigation into the effectiveness of RF Screening to protect Satellite Reception in Burum*, A.H. van den Ende, H.J. Dekker, B. Devecchi, S. Dijkstra, report TNO 2017 R10226, December 2016.

[3] *Co-existentie van Satelliet Grondstation Burum met Broadband Wireless Access netwerken in de 3400-3600 MHz band (unclassified version)*,
ir H.J. Dekker, ir A.H. van den Ende, Ing J. van den Oever, P. Rijsdijk, Ir P.H. Trommelen, TNO report 34886, Januari 2009.

A 5G Deployment scenarios

This Annex is taken from [1] and describes the scenarios developed by TNO.

A hypothetical operator who intends to create an additional 5G-NR layer on his national macro network in the Netherlands has been introduced, with 100 MHz spectrum available in the 3400-3800 MHz band (in accordance with CEPT recommendations)[19]. This operator can have different ambitions and consider different roll-out strategies to achieve a certain ambition. Therefore a framework containing various choices (options) as well as evolutionary steps in time has been defined.

Based on desk research and on insights TNO received in the current perceptions on 5G in the Dutch market through private consultations, several deployment scenarios involving 3400-3800 MHz spectrum have been drafted[20]. These scenarios – at least some of them - could be seen as launch scenarios for any individual operator or as successive steps in an evolutionary process:

- 5G in **four largest cities** (Amsterdam, Rotterdam, Utrecht, Den Haag). We made a distinction between coverage in hot zones only or providing coverage in the entire city;
- 5G in **all urbanized areas** in the Netherlands, in order to reach a high demographic target;
- 5G in the **whole of the Netherlands** (land mass), so aiming for maximum geographical coverage target.

We have identified three phases in the coming decade (period 2020-2028):

Early stage:	Early days of 5G; Adoption is small but growing;
Middle stage:	5G networks have become mature; maximum adoption;
Late stage:	5G networks have further evolved as a consequence of various new applications we do not know (exactly) today.

As the prediction uncertainty regarding likely mobile network deployments and their utilization grows over time, our forecast does not extend beyond 2028.

The evolutionary tendency we allowed in this framework is to move away gradually from coverage towards purely capacity driven deployment, as time progresses. The diagram also shows possible geography dependent network evolutions (from 4 major cities to urbanized areas to national coverage). It is to be noted that the framework does not represent a complete set of possible scenarios. It is intended to capture likely scenarios which we think could become reality.

The baseline for all scenarios is a constellation of sites for a single Radio Access Network (RAN). This fictive constellation is constructed from multi-operator data in the Antenna Register (AR)[21], but then scaled back (per Postcode-4 area) to a grid

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[19] See also CEPT Report 67, July 6th, 2018.

[20] Results of private consultations of mobile operators conducted exclusively by the project manager of this investigation have been used by him in person to check whether initial assumptions concerning likely 5G roll out scenarios were sufficiently realistic.

[21] Source: Non public Antenna Register database, July 3rd 2018 provided by Agentschap Telecom after operators' approval.

which is representative for our single hypothetical operator[22]. In other words, the constellation of our hypothetical operator is the average taken over the four constellations from the AR. The advantage of this approach is that we have used the Antenna Register to derive a grid that already provides a fingerprint of the actual site density distribution in the Netherlands which is also a useful proxy for the geographical distribution of (current) traffic demand. The initial or kick-off 5G presence is based on the current 1800 MHz layer of our hypothetical operator for which we have used insights published by industry and echoed in the Elisa project that the RAN grid of a sparse 5G network based on NR-technology in combination with massive MIMO technology (64T64R) approaches the grid of the 1800 MHz RAN.

With this constellation as baseline, evolutionary growth is assumed and applied in the following ways:

- Growth in 5G presence on sites. After the 1800 MHz grid as initial step, full utilization of the macro constellation has been chosen as a next step, i.e. each site is equipped with a 5G radio (“Robust coverage”);
- Growth in traffic consumed, following from an increasing adoption of 5G based connectivity services;
- Growth in site density of the macro network of 1% per year. We think this is a realistic growth figure for mature macro networks in the Netherlands and is supported by the argument that availability of 3.5 GHz spectrum largely takes away the need for densification for at least 5 years.

Only in the third phase (“Late stage”) we allowed a limited catching up of site densities outside urban/suburban areas on the basis of the expectation that a more versatile utilization of 5G network services in various verticals leads a higher demand of 5G service coverage also in these areas. Also the utilization figures across the different area types have been better equalized.

We applied coarse but conservative spectrum efficiency values[23] to determine the order of magnitude of the extra capacity that can be created with this amount of spectrum using first generation 5G-NR technology. The focus on macro network exploitation and the conservative spectrum efficiency performance assumptions for 5G-NR lead to fairly conservative estimates of the capacity that is created in this way over the period considered. It is certain that in the long run this approach will not suffice. Realistic options which will emerge during that decade are:

- Deployment of the next generation massive MIMO technology with higher numbers of elements (e.g. 256T256R) leading to higher spectrum efficiencies of the existing capacity layer on the Macro network;
- Densification, but mainly through the use of small cells. The use of C-band spectrum both in the macro and micro layers pose spectrum management challenges. Hence, this may have to be done in another (higher) band;
- Exploitation of higher bands in which case the 26 GHz would be the first logical candidate. This band is particularly suitable for hot spots areas covered by small cells. Alternatively the operator could put more emphasis on using license free spectrum where possible.

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[22] We have not used actual site locations in our simulations but rather site densities per postcode area (PC-4).

[23] The IMT2020 Performance requirements on Spectrum Efficiency have been adopted. Technology and more particularly massive MIMO will allow operators to push the bar considerably higher.

Given the critical attitude we generally see in the market concerning the use of small cells in outdoor settings, we have not made the small cells deployment part of the “natural” 5G roll out scenarios. Small cells are however relevant as a possible mitigation measure in the co-existence matter.

The whole set of 5G scenarios in our framework is depicted in the Figure A.1 below. The arrows connecting the various scenario instances indicate possible transitional choices an operator could make over time. Their purpose in the diagram is only to underline that such choices exist and a single predetermined roll-out strategy simply does not exist.

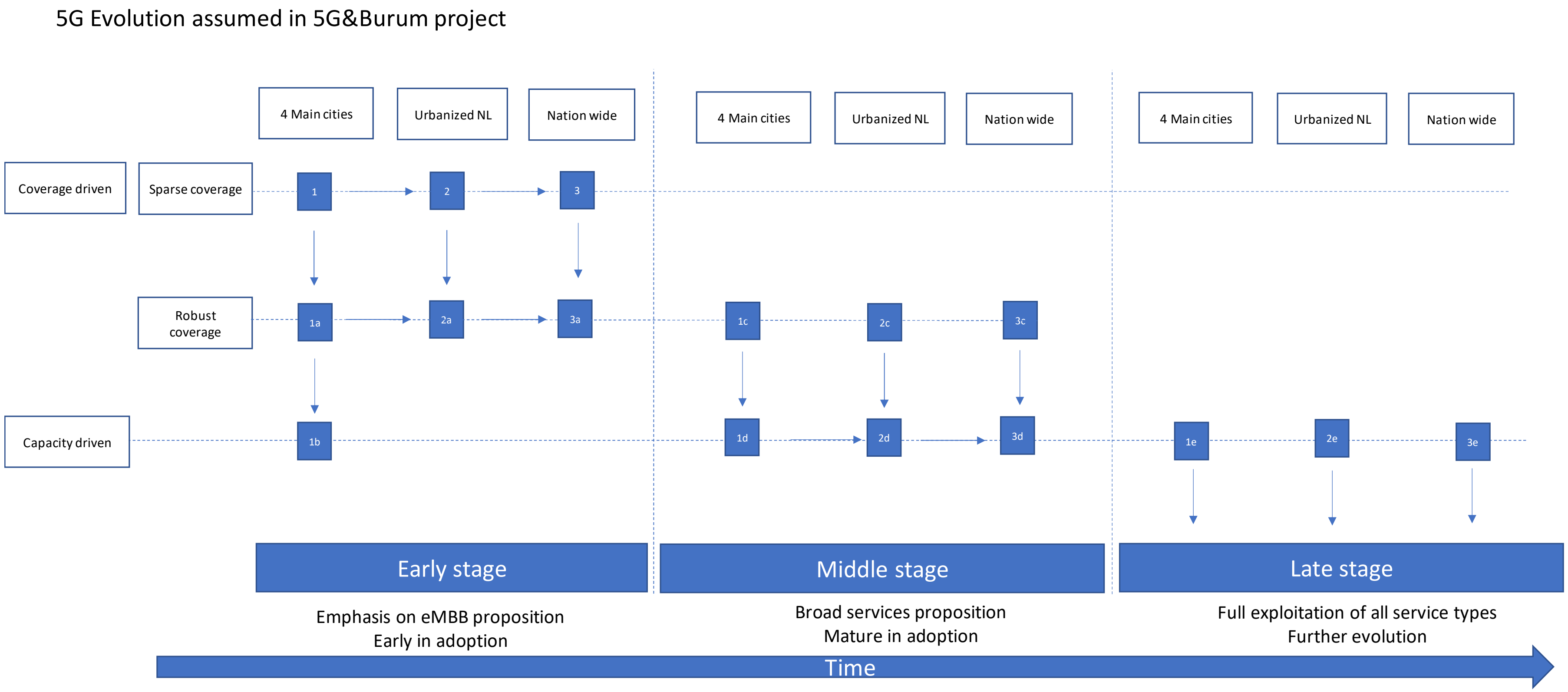

Figure A.1: Possible network evolutions and network instances, during three successive stages

The table below contains the 16 defined scenario profiles. The commonality in geographical scope (4 main cities/urbanized NL/Nationwide) has been visualized using a colour scheme.

Table A.1 Overview of 5G scenario profiles defined

Scen.	Stage	Accessible sites	5G presence (%)	Average Traffic Capacity (GB/s/km2)	Average Consumed Capacity (%)
1	Early stage	692	63	1,5	4.6
2		2416	62	0,3	4.1
3		5005	57	0.1	4.0
1a		692	100	2.3	4.6
2a		2416	100	0.5	4.1
3a		5005	100	0.2	3.3
1b		692	100	2.4	4.6
1c	Middle stage	692	100	2.3	46
2c		2416	100	0.5	41
3c		5005	100	0.2	17
1d		720	100	2.4	46
2d		2514	100	0.6	41
3d		5210	100	0.2	33
1e	Late	762	100	2.5	48
2e		2673	100	0.6	44
3e		5690	100	0.2	42

The table shows that the assumed gradual expansion of the macro network is not enough to see a significant increase in the average network capacity per km/2. The traffic consumption increases as the adoption of 5G based services grows over the years. As the table indicates, we have assumed 5G presence on all macro sites within the intended services area, except for the initial stage where we have assumed a sparse deployment.

Scenario 3E in our framework has a particular relevance because this scenario has been chosen to derive the mitigation effort in the 5G-Burum SAS co-existence case.

Assumed 5G system configuration and their modelling
For the sake of the co-existence analysis we have assumed a 5G system configuration which is typical for a macro network deployment, with the following parameterization:

Table A.2: Nominal 5G system configuration assumed in our studies

Feature	Value
Band	3.400-3.800 MHz
Channel	100 MHz
Transmitter power	51 dBm
Antenna system	Conventional (reference purposes; 17 dBi) mMIMO 64T64R (optional; 24 dBi)
Sectors	3
Antenna height	25 meters (sub-)urban 35 meters (rural)
DL/UL	DL only
Load	Different but fixed settings
Inter Site Distance	Follows from the Antenna Register

With respect to the base stations' radiated power, the remark applies that we did not take the maximum allowable 'in block' radiation level (according to EC Decision 2014/276/EU[24]) of 68 dBm/5MHz, which equals 81 dBm over 100 MHz. In case of massive MIMO, the maximum radiation level in our simulations may be up to 75 dBm over 100 MHz.

The load is an important parameter when it comes to interference impact. We have assumed a maximum (theoretical) carrier load of 100% as the upper bound, which effectively resembles a downlink only situation[25]. Lower, more realistic loads have been applied in the scenarios with the important assumption that the load is distributed equally across all available resource blocks.

We also considered the deployment of small cells in our analysis but applied a modified approach. Small cell deployments can be characterized by smaller inter site distances, lower transmitter powers and (much) lower antenna heights, typically relevant to traffic demanding urban areas. We evaluated the interference impact on each of these aspects separately. As a sanity check, we then conducted a separate small scale simulation to be able to compare (for the same city area) the difference in interference impact between the macro and small cells deployment where these aspects are combined.

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[24] Source: EC, *Commission Implementing Decision on amending Decision 2008/411/EC on the harmonization of the 3 400-3 800 MHz frequency band for terrestrial systems capable of providing electronic communications services in the Community*, 2014/276/EU, 2 May 2014.

[25] A downlink only use of the 3400-3800 MHz poses limitations in the use of mMIMO and in the exploitation of uRLLC type of services.