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TNO report

TNO 2018 R11156 | 1.0

Co-existence of 5G mobile networks with C-Band Satellite Interception in Burum

Date	30 November 2018
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Copy no	
No. of copies	
Number of pages	186 (incl. appendices)
Number of appendices	8
Sponsor	Ministry of Economic Affairs and Climate Policy
Project name	Co-exstence 5G and Burum
Project number	060.33165

Management Samenvatting

Title :	Co-existentie van 5G mobiele netwerken met C-band satelliet interceptie in Burum
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Date :	30 November 2018
Contract nr. :	201804006
Reportnr. :	TNO 2018 R11156

Achtergrond

Eén van de in Europa aangewezen frequentiebanden voor de introductie van 5G mobiele netwerken is de 3400-3800 MHz band. Deze band maakt echter ook deel uit van de zogenaamde C-band (3400-4200 MHz), een internationale band voor satellietcommunicatie. Interceptie van satellietcommunicatie, die in andere delen van de wereld plaatsvindt, verschaft de Nederlandse overheid inlichtingen die relevant zijn voor de staatsveiligheid. De interceptiefaciliteit is gevestigd in Burum. Uit eerdere studies is bekend dat Broadband Wireless Access (BWA) netwerken in deze band die in Nederland of in omringende landen zijn uitgerold, nauwelijks kunnen co-existeren
(samenleven) met dit zeer gevoelige interceptiesysteem. Teneinde de faciliteit te beschermen is in 2011 specifieke regelgeving van kracht geworden voor deze band zodanig dat deze BWA-netwerken of netwerken met vergelijkbare radiokarakteristieken niet worden toegestaan boven de HOL-008 demarcatielijn (Amsterdam-Zwolle). Beneden deze lijn zijn deze netwerken toegestaan, indien aan bepaalde radiotechnische randvoorwaarden wordt voldaan. Tot vandaag de dag zijn er vergunningen uitgegeven aan individuele bedrijven voor lokale netwerken. Deze vergunningen lopen uiterlijk tot 2026.

Er is aanzienlijke druk op een tijdige introductie van 5G in Europa en dus ook in Nederland, gegeven de verwachte positieve maatschappelijke en economische effecten van deze technologie en de verwachte gunstige impact op een aantal hedendaagse maatschappelijke uitdagingen. Deze ambitie vergt toegang tot de 3,5 GHz pionierband, maar dit is in strijd met de huidige beschermingseisen voor Burum, een faciliteit die de Nederlandse overheid beschouwt als een essentieel instrument voor inlichtingenvergaring dat voor de komende tijd relevant blijft voor nationale veiligheidsdoeleinden. De telecomsector heeft zorgen geuit over een duidelijk en actueel risico dat de introductie van 5G hierdoor wordt vertraagd. Er is daarom sprake van druk vanuit verschillende belanghebbenden om te bepalen hoe co-existentie kan worden bereikt, waarbij rekening wordt gehouden met beide belangen. Het is belangrijk hierbij aan te tekenen dat de 3,5 GHz-band niet als enige maar wel als de belangrijkste 5G pionierband wordt gezien.

Het Ministerie van Economische Zaken en Klimaat (hierna genoemd MinEZK) heeft de Tweede Kamer toegezegd te rapporteren over mogelijke oplossingen en heeft daarom voor dit doel enkele onderzoeken geïnitieerd, in nauwe samenwerking met het Ministerie van Defensie (hierna genoemd MinDef) die de inlichtingendiensten vertegenwoordigt. TNO is in de zomer gevraagd een onderzoek naar de co-existentie uit te voeren, op basis van de volgende twee hoofdonderzoeksvragen:

1. Wat is de te verwachten radiotechnische impact van de uitrol van 3GPP gestandaardiseerde 5G netwerken in de 3,5 GHz band, op de wijze zoals in

Nederland mag worden verwacht, op de prestaties van de Interceptiefaciliteit te Burum?
2. Welke technisch haalbare maatregelen kunnen worden geïdentificeerd die het mogelijk maken om 5G netwerken en C-band satellietinterceptie te laten co-existeren?

Proces
TNO heeft literatuuronderzoek, informatie uit een eigen consultatie van operators, antwoorden op specifieke vragen aan 5G technologie-aanbieders en eigen achtergrondkennis gecombineerd om tot opties te komen voor de toekomstige uitrol van 5G gebaseerde mobiele netwerken in Nederland. Dit heeft geresulteerd in een scenarioraamwerk dat is gebruikt voor de impactanalyse. De impactanalyse is uitgevoerd met als doel om tot voorspellingen te komen over de ernst van 5G emissies op Burum en van de mate van vereiste radiotechnische ontkoppeling om co-existentie te bewerkstelligen. Mogelijke mitigatiemaatregelen zijn geïdentificeerd voor beide toepassingen en zijn getoetst op hun haalbaarheid. Dit was niet gericht op het specifiek ontwerpen van oplossingen maar om vast te stellen of via technische maatregelen co-existentie zou kunnen worden bereikt. Vanuit de resultaten van de impactanalyse en mitigatietoets zijn we in staat om conclusies te trekken over co-existentiemogelijkheden op de middellange en lange termijn. Als onderdeel van dit onderzoek zijn metingen uitgevoerd waarmee de betrouwbaarheid van onze modellen kon worden verbeterd.

Bevindingen
<u>Bevindingen ten aanzien van Vraag 1</u>
De prestaties van de Interceptiefaciliteit Burum in zijn huidige vorm zullen nadelig worden beïnvloed indien het publieke mobiele netwerken wordt toegestaan spectrum te gebruiken in de 3400-3800 MHz band. Dit betreft in eerste instantie netwerken in Nederland, maar de interceptiefaciliteit in Burum is niet ongevoelig voor netwerken in het buitenland, en dan met name in Duitsland, die deze band gaan gebruiken. Niet het bestaan van deze netwerken, maar vooral hun benutting zal storing veroorzaken in de ontvangstsystemen van de Interceptie-faciliteit in Burum met als gevolg verlies van interceptieproductie/productiviteit. De omvang van de impact hangt sterk af van waar, hoe en met hoeveel spectrum in deze band 5G technologie wordt toegepast. Het gehele co-existentieprobleem is in de technische zin zeer stochastisch van aard en kan niet in zijn totaliteit worden gemodelleerd. Daarenboven is er een inherente onzekerheid ten aanzien van uitrolopties van individuele operators en ten aanzien van hoe netwerken zich op termijn zullen ontwikkelen. Dit betekent dat conclusies over impact betrekking hebben op de belangrijkste effecten die we verwachten en dat er marges in acht moeten worden genomen bij het voorspellen van de toekomst.

Onze verwachting is dat concurrerende operators een 3,5 GHz spectrumvergunning zullen gebruiken om beschikbare 5G technologie snel in hun netwerken te introduceren (in de vorm van een 5G-laag), gedreven door capaciteitsvraag en door commerciële doelen om nieuwe, 5G gebaseerde dienstverlening in de markt te introduceren. De uitrol van 5G-technologie kan initieel in de steden plaatsvinden waarna uitbreiding plaatsvindt naar andere delen van het land. Echter, een directe landelijke uitrol behoort ook tot de mogelijkheden. In onze analyse hebben we diverse, waarschijnlijke opties in een tijdsvolgordelijk scenarioraamwerk opgenomen, allen gebaseerd op een te verwachten werkwijze waarin operators hun bestaande infrastructuur met additioneel spectrum zullen gebruiken, alvorens zich op een lastige verdichting van sites te richten. Derhalve is in ons 5G-scenarioraamwerk sprake van een beperkte groei van deze infrastructuur in de komende 10 jaar.

Ongeacht de wijze van uitrol van een “5G-laag” zal de feitelijke impact op de interceptiefaciliteit in Burum voornamelijk worden bepaald door de benuttingsgraad van deze laag in termen van downlink verkeer dat er in wordt afgehandeld. De benuttingsgraad zal naar schatting groeien met een jaarlijkse factor van ca. 1.4-1.5, wat een conservatieve aanname is voor Nederland en ook voor deze band. **Onze beoordeling is dat voor alle scenario’s uit ons scenarioraamwerk het productieverlies de normwaarde van 0,0038% zal overschrijden,** een normwaarde die in 2008 is geformaliseerd voor de Interceptiefaciliteit te Burum. Het meest volwassen/ontwikkelde scenario uit ons raamwerk, landelijke 5G-uitrol tot 20 km afstand van Burum met een indicatieve tijdaanduiding van 2028, leidt tot een productieverlies die de 50% overstijgt. De impact neemt evident verder toe voorbij de scope van ons verondersteld 5G scenarioraamwerk.

Bevindingen ten aanzien van Vraag 2

We hebben een reeks van mogelijke mitigatiemaatregelen onderzocht en beoordeeld, maatregelen die zowel mobiele netwerken als ook de Interceptiefaciliteit Burum aangaan. Elke maatregel heeft een bepaalde verwachte mitigatie-effectiviteit, impact op de dienstverlening en een bepaalde mate van technologische volwassenheid c.q. haalbaarheid. Uit deze beoordeling hebben we maatregelen geïdentificeerd die we op zichzelf haalbaar achten, qua radio-ontkoppelingspotentieel en technologische realiseerbaarheid of beschikbaarheid, in de meeste gevallen binnen een tijdsperiode van 3 jaar vanaf heden. Dat gezegd hebbende, zien we op grond van deze analyse geen enkele realistische mitigatiestrategie waarmee de normwaarde uit 2008 voor het productieverlies zou kunnen worden gehaald.

Co-existentie is mogelijk in het grootste deel van het land in de komende tijd

Het is uitdagend maar technisch haalbaar door een combinatie van maatregelen aan beide zijden om co-existentie tussen 5G-netwerken en de Interceptiefaciliteit Burum in het grootste deel van het land mogelijk te maken voor een periode van 5 tot 7 jaar na de introductie van 5G netwerken in deze band, welke we in Nederland verwachten rond 2021-2022. Daarbij wordt het productieverlies beneden de ca 1% (grootte-orde) gehouden. Dit veronderstelt dat gedurende deze periode de relatieve bijdrage van 5G-netwerken in Duitsland qua storing beduidend kleiner zal zijn dan de bijdrage van netwerken op Nederlands grondgebied.

Onopgelost probleem in meest noordelijke deel van Nederland

Een oplossing voor de situatie in het noorden van het land is moeilijk omdat de gezamenlijke mitigatie-eis exponentieel stijgt wanneer men met 5G Burum dichter dan ca. 50 km nadert. Dit zou normaliter vragen om een exclusiezone van deze omvang. Het negeren van deze exclusiezone is niet aan te bevelen omdat de resulterende gezamenlijke mitigatie-eis niet meer op realistische wijze kan worden gehaald. **Een exclusiezone van deze omvang (ca. 14% van de Nederlandse landmassa) die steden als Groningen, Leeuwarden en Assen omvat, zou opnieuw een demarcatielijn introduceren hoewel deze beduidend dichter bij Burum ligt dan de huidige HOL-008 lijn**. De enige effectieve radiotechnische oplossing die we zien in deze band waarmee een permanente exclusiezone met een straal van 50 km wordt vermeden, is de toepassing van een splitsing in het frequentiegebruik, wat betekent dat de gehele 3400-3800 MHz band (andere terrestrische gebruikers buiten beschouwing gelaten) zou moeten worden opgesplitst tussen de beide toepassingen. Dit zou de exclusiezone tot ca. 20 km doen reduceren. Deze frequentieseparatie, hetzij in een ‘domme’ of ‘slimme’ variant, introduceert diverse moeilijkheden voor beide toepassingen, ook van niet-technische aard. TNO verwacht daarom dat deze optie moeilijk zal kunnen worden geaccepteerd door alle belanghebbenden als een uitkomst om de exclusiezone te verkleinen. Het niet-accepteren hiervan maakt een permanente 50 km exclusiezone onvermijdelijk, met de consequentie dat in dit deel van het land 5G-dienstverlening pas op een later moment mogelijk is (via andere banden) en diensten die niet vergelijkbaar zullen zijn met de dienstverlening die elders in Nederland kan worden geboden. Onze conclusie is daarom dat de kwestie met de exclusiezone onopgelost is gebleven in ons onderzoek. We hebben de kwestie geïsoleerd en onderstaande bevindingen, die zijn gebaseerd op de aanname van een 50 km exclusiezone, laten dit punt verder buiten beschouwing.

Voorstel om de mitigatielast te delen
We stellen voor om de gezamenlijke en uitdagende mitigatielast gelijkelijk te verdelen over beide toepassingen, gegeven het feit dat aan beide zeer verschillende toepassingen een groot maatschappelijk belang kan worden toegekend en gegeven het zeer duidelijke onderscheid tussen exploitatiedoelen en verantwoordelijkheden tussen beide. In spectrum management termen krijgen beide toepassingen dan een co-primaire status en dragen een gelijkwaardige verplichting om co-existentie mogelijk te maken. De hierna volgende bevindingen zijn op dit beginsel gebaseerd.

Mitigatie aan de 5G zijde
Haalbaar geachte maatregelen die kunnen worden toegepast op 5G gebaseerde netwerken beneden deze nieuwe demarcatielijn zijn de toepassing van adaptieve antennetechnologie in combinatie met specifieke op de antennes van de basisstations gerichte aanpassingen zoals tiltaanpassing, verlaging van antennehoogten en reductie van de antenneversterking specifiek richting Burum. Het gebruik van *small cells* is aanbevelenswaardig waar dit mogelijk is. Welke maatregel waar toe te passen achten we geheel aan de mobiele operator om te beslissen. De mobiele operator wordt door deze maatregelen geconfronteerd met een resulterende penalty in de vorm van additionele verdichting om een zeker a priori voorgenomen niveau van *quality of service* en capaciteit te kunnen bewerkstelligen in het gehele gebied waar het netwerk dienstverlening aanbiedt. We verwachten daarom dat de mitigatie-eis welke in de orde van 20 dB ligt, een duidelijke impact zal hebben op de kosten van de uitrol van 5G en ook zal leiden tot een meer selectieve benadering ten aanzien van de uitrol van deze technologie in Nederland.

Mitigatie aan Burumzijde
Haalbaar geachte maatregelen die door de Interceptiefaciliteit Burum kunnen worden toegepast richten zich op de schotelantennes. TNO acht het haalbaar om in de bestaande constellatie satellietschotels te verbeteren zodanig dat een mitigatiewinst in de orde van 10 dB kan worden behaald. We beschouwen een eventuele concessie aan de 2008-norm van 0,0038% door een verhoging naar bijvoorbeeld 1% of naar elke andere waarde ook als een bijdrage aan de mitigatie-eis voor Burum. In dat opzicht zijn technische mitigatiemaatregelen en een afgezwakte productieverliesnorm uitwisselbaar. Het grote voordeel van een op de antenneschotels gerichte aanpak is dat de faciliteit ook minder gevoelig wordt voor interferentie afkomstig uit het buitenland. Dit neveneffect is niet aan de orde aan de 5G-zijde. Alternatieve interceptieconcepten zijn eveneens beschouwd waarvan enkele een hoger mitigatiepotentieel hebben in vergelijking met maatregelen gericht op de antenneschotels. Dergelijke alternatieven zien we als mogelijke lange-termijn oplossing (voorbij 2030) maar niet geschikt om de uitdaging op middellange termijn het hoofd te bieden (volgend decennium).

Co-existentie evaluatie nodig voor 2030
Gezien het feit dat de voorwaarden in de te veilen vergunningen moeten worden gespecificeerd om zodoende de verkrijger van een vergunning voldoende zekerheid te bieden, moet de maximale mitigatieverplichting worden gedefinieerd als onderdeel van de vergunning. Voorspelling van wat de mitigatieverplichting tegen het jaar 2040 moet zijn is niet haalbaar omdat dit geheel afhangt van de wijze waarop mobiele netwerken zich verder zullen

gaan ontwikkelen in het volgende decennium. Daarbij is het zeer onzeker of deze zwaardere verplichting űberhaupt te dragen zou zijn door beide toepassingen (zie ook passage over lange termijn perspectief). Een pragmatische maar belangrijke keuze is om het jaar 2030 in dit opzicht als de volgende mijlpaal te beschouwen waarvoor dit rapport enige houvast biedt. We stellen daarom voor om een co-existentie arrangement op te zetten waarvan wordt verwacht dat het tot ver in de twintiger jaren werkt. Tegen 2030 dient een evaluatie te zijn uitgevoerd waarbij de gehele co-existentie situatie wordt herzien en besluiten zijn genomen rond deze kwestie, betreffende het daarop volgende decennium (2030-2040) of voor de periode tot aan de datum waarop de uit te geven 5G vergunningen aflopen, als dat eerder is.

Lange-termijn perspectief (>2030) betreffende co-existentie
Het lange-termijn perspectief met betrekking tot de co-existentie van beide toepassingen is op zijn minst zeer onduidelijk. Met de huidige maar aangepaste faciliteit te Burum is de verwachting dat de groeiende mitigatiedruk in het volgende decennium, mede veroorzaakt door gerelateerde mobiele netwerk ontwikkelingen in het buitenland (in het bijzonder Duitsland), een heroverweging van de co-existentie noodzakelijk zal maken. Op dit moment zijn er teveel onbekendheden om nu te voorspellen dat co-existentiemogelijkheden op Nederlands grondgebied kunnen worden verlengd tot bijvoorbeeld 2040 door de introductie van alternatieve interceptietechnieken. Volledige *phased array* oplossingen hebben een zeer groot potentieel maar zijn eveneens zeer kostbaar en vragen substantiële R&D en engineering inspanningen. De kosten-baten verhouding die kan worden verwacht in dit specifieke geval kan met de huidige kennis nog niet betrouwbaar worden ingeschat.

Aanbevelingen

Onze hieronder geformuleerde aanbevelingen dienen te worden gezien binnen de scope van dit technische onderzoek naar mogelijkheden voor co-existentie van beide toepassingen. Het is volstrekt helder dat deze aanbevelingen zijn onderworpen aan de politieke duiding van onze conclusies.

Hoofdaanbevelingen
Onze eerste hoofdaanbeveling is om de opzet van een middellange termijn co-existentie arrangement te overwegen dat intreedt nadat de 3,5 GHz vergunningen zijn verleend en dat in eerste instantie tot hooguit het jaar 2030 voortduurt. Dit arrangement veronderstelt een gedeelde mitigatieverantwoordelijkheid tussen beide toepassingen en verzekert tenminste de co-existentie van de Interceptiefaciliteit Burum met 5G netwerken in Nederland tot op 50 km afstand van Burum. Dit vergt een *Mid-Life Upgrade* van de Interceptiefaciliteit en de opzet van een *Licensed Shared Access* (LSA) raamwerk. Dit raamwerk biedt het regelgevend kader om adequate co-existentie tussen beide toepassingen te verzekeren. Het LSA-raamwerk wordt uitgevoerd door Agentschap Telecom waarbij een per vergunning vastgesteld maximaal stoorniveau (plafond) van een 5G gebaseerd mobiel netwerk niet mag worden overschreden. In dit interferentieplafond dient te zijn verdisconteerd de 23 dB maximale mitigatielast welke aan 5G gebaseerde mobiele netwerken in deze band wordt opgelegd, conform onze bevindingen. Deze plafondwaarde en hoe deze dient te worden gemeten, dient zeer helder te zijn gedefinieerd. Deze dienen deel uit te maken van de vergunningsvoorwaarden.

Direct aan deze aanbeveling is het advies gekoppeld om een evaluatie van dit co-existentie arrangement te plannen, welke voor 2030 dient te hebben plaatsgevonden. De evaluatie is om vast te stellen of het arrangement in zijn gekozen vorm kan worden verlengd tot in het volgende decennium, of niet. Dit hangt grotendeels af van de vraag hoe tegen die tijd 5G gebaseerde netwerken zich zullen hebben ontwikkeld in Nederland en daarbuiten

(Duitsland), hoe de roadmap voor deze netwerken voor het opvolgende decennium (2030-2040) er uitziet en ook wat t.z.t. de visie is op C-band satellietsignaalinterceptie voor diezelfde periode.

In samenhang met deze hoofdaanbeveling zijn de volgende specifieke aanbevelingen aan de orde:

- TNO beveelt de betrokken Ministeries en Agentschappen (Joint Sigint Cyber Unit en Agentschap Telecom) aan om in samenwerking met tenminste JSCU-Burum en de operators **een LSA-raamwerk te definiëren om de toekomstige co-existentie van Burum met nationale mobiele netwerken te bewaken**. Een essentieel onderdeel hiervan is een Interferentie Monitoring- en Waarschuwingssysteem zoals voorgesteld in dit rapport. Een tweede onderdeel is een terugkoppelingskanaal richting de mobiele operators voor situaties waarin het voornoemde interferentieplafond wordt overschreden (met of zonder veiligheidsmarge).

- TNO beveelt de betrokken Ministeries en Agentschappen aan om de periode totdat de nationale vergunningen worden geveild te gebruiken om **te leren van praktische 5G netwerken op kleine schaal** waarvoor experimenteervergunningen kunnen worden aangevraagd. Het toestaan van dergelijke experimenten ook boven de HOL-008 lijn moet worden overwogen zolang voldoende garanties kunnen worden ingebouwd om de interceptiefaciliteit in Burum tegen schadelijke interferentie te beschermen. Dit vergt uiteraard de betrokkenheid van de JSCU.

- TNO beveelt de overheid aan om een **Mid-Life Upgrade programma voor de Interceptiefaciliteit Burum (Burum 2.0)** te definiëren, begroten en uit te voeren, waarvoor dit rapport een eerste voorstel op hoofdlijnen bevat. Als dit programma voor 2022 kan zijn gerealiseerd, dan zal de faciliteit zijn voorbereid voor de eerste 5-7 jaar na de introductie van 5G-technologie in mobiele netwerken. Het ontwerpdoel voor dit programma is een minimale interferentieonderdrukking van 10 dB, zodanig dat een hoge mate van operationele vrijheid van de faciliteit behouden blijft. Ordegrootte van de kosten van dit programma wordt geraamd op 10 MEUR.

- TNO beveelt de overheid en de interne belanghebbenden van de Interceptiefaciliteit Burum aan om na te denken over de toekomst van Burum als instrument voor inlichtingenvergaring gebaseerd op **C-band satelliet-signaalbronnen**. Ruim voor het jaar 2030 is ten aanzien van deze specifieke activiteit een strategie nodig, waarbij ontwikkelingen in mobiele communicatienetwerken evenals relevante technologieën voor interceptie worden meegenomen. Gedurende de Burum 2.0 exploitatiefase dient deze strategie in uitvoering te zijn, vooruitlopend op een onontkoombare degradatie in de prestaties van de Interceptiefaciliteit Burum richting 2030.

Onze tweede hoofdaanbeveling aan de overheid is om te kijken naar het probleem in het noorden van Nederland waarvoor geen gemakkelijke oplossing te vinden is. Ons voorstel is om een gestructureerde en goed voorbereide workshop te organiseren voor alle belanghebbenden (inclusief satellietcommunicatie-aanbieders maar ook de industrie) in een poging om het minst problematische compromis te vinden. Als deze gevonden wordt, dan kan dit resulteren in een aanbeveling die kan worden meegenomen in de politieke besluitvorming. Andere strategieën om dit op te lossen dienen ook te worden overwogen.

Aanvullende aanbevelingen

Tot slot zijn de volgende aanvullende aanbevelingen aan de orde:

- TNO beveelt MinEZK aan om inzicht te verkrijgen in de implicaties van de mitigatie-eis zoals voorgesteld in dit rapport op de ontwikkeling van mobiele netwerken op basis van 5G-technologie. Belangrijke aspecten zijn de impact op de uitrolstrategie, additionele kosteneffecten en resulterende impact op de dienstverlening.
- TNO beveelt MinEZK en AT aan om de 3,5 GHz meetcampagne de komende drie jaar te hervatten met geografisch verspreide bakens in de 3,5 GHz band (bijvoorbeeld 1 in elke provincie) met drie doelstellingen:
    1. Teneinde een *Proof of Concept* Interferentie-monitoring oplossing te Burum te testen, zoals voorgesteld in dit rapport, en dat deel moet gaan uitmaken van het LSA-raamwerk;
    2. Om bij te dragen aan een beter begrip van de specifieke propagatie-effecten in deze band in Nederland. Deze effecten spelen een rol in dit co-existentie dossier en worden nog niet volledig begrepen, hetgeen substantiële onzekerheidsmarges introduceert bij de impact assessment en bij de mitigatie;
    3. Om bij te dragen aan de productie van wetenschappelijke propagatiedata die kan worden gebruikt in een initiatief om de voorspelbaarheid van bijzondere propagatiecondities te verbeteren (zie volgende punt).
- Mobiele operators, AT, KNMI en TNO kunnen gezamenlijk bepalen hoe met de opgedane inzichten in dit onderzoek de voorspelling van bijzondere propagatiecondities kan worden verbeterd en omgezet kunnen worden in een ‘radioweerbericht’ waar mobiele operators gebruik van kunnen maken.

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[1]. This band is however also part of the so called C-band, an international band for satellite communications, which is defined between 3400 and 4200 MHz. Interception of such communications which take place in other parts of the world provides the Dutch government relevant intelligence data. The Interception Facility is located in Burum. From past studies it became known that Broadband Wireless Access networks which would operate in this band and are deployed in the Netherlands or even in surrounding countries could hardly coexist with this high sensitivity Interception system. In order to protect the Facility, in 2011 regulatory restrictions were applied to this band in the Netherlands such that these BWA networks or networks with equivalent radio characteristics would not be allowed above the HOL-008 demarcation line, and be allowed below that line only if certain technical conditions were met. To date, licenses have been granted to individual organizations for local networks. These licenses expire in 2026 at the latest.

There is substantial pressure on the timely introduction of 5G in Europe, and henceforth in the Netherlands, given the growing mobile traffic capacity demand and expected positive societal and economic effects of specifically this technology generation This 5G ambition would require access to the 3.5 GHz pioneer band, but this is in conflict with the protection policy for Burum, a facility that the Dutch government considers as an essential asset for Intelligence gathering and which remains relevant for national security purposes for the foreseeable future. The telecommunications sector has expressed concerns about a clear and present risk of a delayed introduction of 5G due to this issue. Hence there is political pressure to determine how this can be resolved taking into account both interests. It is important to note that the 3.5 GHz band is not the only 5G pioneer band, but it is generally considered to be the most important one.

1.2 Conduct of investigation

The Ministry of Economic Affairs and Climate Policy (hereafter noted as MinEZK) had promised to report to Parliament on possible solutions and initiated investigations to this end, in close cooperation with the Ministries of Defence (hereafter noted as MinDef) and Home Affairs. In this context TNO has been asked to conduct such an investigation, in a limited time frame. The two main research question we have investigated are:

1. What is the expected radio technical impact of deployed 3GPP standardized 5G networks in the 3.5 GHz band, as assumed to be likely for the Netherlands, upon the performance of the Interception Facility at Burum?

2. Which technically viable measures can be identified to allow 5G network deployments and C-Band Satellite Interception to coexist?

[1] This notation is used or abbreviated as “3.5 GHz”

This unclassified report contains the insights and results obtained. It is intended to provide all relevant stakeholders adequate insight in the need for mitigation measures to resolve the co-existence issue between 5G mobile networks and the C-band Satellite Interception Facility at Burum, and informs them about promising directions of solutions for mitigation on the mid as well as long term, in terms of effectiveness and practical technical feasibility. In addition to this report, there is a separate concise report which contains classified information relevant to this work. Upon request the report also contains a more elaborate treatment on 5G developments[2].

The investigation has been guided by an External Advisory Board with representatives from MinEZK, MinDef, Agentschap Telecom (AT) and the Joint Sigint Cyber Unit (JSCU). Prof P.G.M. Baltus associated with the TU Eindhoven and active in the area of RF Electronics and system design acted as independent academic member in this Board. CMS conducted an assessment of possible anti-competitive elements contained in the report text.

1.3 Interpretation of the problem

Any mobile communications network applies radio transmission techniques to achieve wireless connectivity between mobile user devices (smart phones, tablet and machines) and the fixed infrastructure. The growth in demand for mobile communications and the fast development of the applicable technologies has resulted in the nationwide deployment of successive generations of mobile networks, with each new generation equipped with more capabilities than the previous one. This growth in demand required denser deployments of base stations (radio towers) especially in urban areas, and more radio spectrum (frequencies). This spectrum expansion which is coordinated internationally touches upon legacy uses in various frequency bands. In this specific case we are dealing with a new mobile network generation (5G) arriving, and for which new suitable spectrum was sought. A few years back, the EC embraced the 5G development and, in line with worldwide developments, announced the 3400 – 3800 MHz band as the recommended pioneer band for this new generation. The preference for this band can be explained partly from the fact that for over a decade this part of the world (Europe and Africa) this band or at least of it was already in use in Europe for nomadic Broadband Wireless Access (BWA) applications while at the time it was earmarked in Africa for future mobile communications. BWA is related to mobile communications as we know it today, with WiMAX as dominant technology at the time. In the satellite communications world, this band is recognized as a substantial part of the so called C-band. C-Band satellite communications is a legacy, and still widely used, application. This is why interception of remote satellite communications, which is a passive use of this band and conducted in Burum (Friesland) is still considered by the Dutch government to be an essential activity in the context of national security. Co-existence of multiple uses in the same frequency band in a way that mutual harmful interference can be avoided is a widely accepted practice, but whether it is actually possible depends on various factors and needs to be assessed on a case-by-case basis. Passive systems such as Interception systems are built to be much more sensitive than regular receiver

[2] This elaborate treatment does not in any way imply a bias of the research team towards the mobile communications application.

systems, so the co-existence issue at hand goes beyond what is typically considered with satellite receiver systems. In other words, a satellite interception receiver could be affected by another active transmitter at much larger distances than would be the case with a normal receiver. As explained earlier in this chapter, investigations in 2008 into the co-existence of BWA and Satellite Interception indeed revealed a potential radio technical conflict in case of BWA deployments in the Netherlands, which led to Netherlands specific policy adjustments for this band which still apply. As the BWA deployment as such did not yet exist on a national scale at the time, impact estimations based on modelling and prediction, supported by validation activities, were inevitable. This is a common method in spectrum management.

The emerging 5G generation mobile networks is different from BWA networks in various ways which makes it important to reconsider the matter. On the one hand, 5G networks are expected to become ubiquitous, providing coverage and adequate capacity basically (almost) everywhere and are expected to be used very intensively by the masses. In case of BWA, the assumed deployment did not go beyond coverage in cities, addressing the communication needs for nomadic users. Secondly, 5G has higher spectrum needs, so much larger portions of the C-band are claimed for successful 5G deployments in a multi-operator market constellation. On the other hand, 5G technology brings more sophistication regarding the type of antennas used, the smartness in the network regarding adaptability to specific conditions. Also the ideas of operators about 5G deployment models are not necessarily identical to those with BWA. The large flexibility which 5G offers brings additional degrees of freedom in network deployment and deployment evolution. Looking at the Burum side, the existing system deals with limitations in its flexibility to cope with interference and has to maintain KPI's which apply to this Facility. Past exercises have made clear that mitigation at this end is far from trivial without accepting performance degradation. Nevertheless, we have to again look into what the 'share of Burum' could be in resolving co-existence issues with 5G.

Radio propagation is a physical and fairly complex phenomenon which plays a very influential role in this matter. The interaction of radio waves with terrain, buildings and atmosphere turns radio propagation into a process with a substantial amount of randomness. The stronger the radio signal attenuates over distance, the shorter possibly conflicting systems need to be separated from each other in geographical distance to achieve sufficient *radio decoupling*. The presence of very rough terrain can help to ease a radio co-existence situation. In this respect, the Netherlands has two disadvantages over many other countries. First, this country is generally flat and it is characterized by many (some large) water surfaces which are propagation friendly and henceforth increases interference risks. On the other hand, cities, that will require more densified 5G networks to meet demand, are inherently "rough" through the presence of buildings. So, depending on antenna heights applied, signals could be easily blocked already at very short distances and subsequently do not easily "escape" from there. Hence, it is important to make a distinction between propagation in urban, built up areas (local terrain effects) and propagation over larger distances because the mechanisms and the way to deal with them are very different.

1.4 Approach

The reliability of the impact assessment depends on the degree of validation applied to the predictions involved. Validation has been conducted in this investigation but not to the full extent, due to fundamental and practical limitations. 5G networks do not actually exist yet and the cost/benefit ratio of using of small scale 5G demonstrators (e.g. for piloting purposes) is poor. Improving accuracy in propagation predictions require extensive and long term measurements before they have sufficient statistical relevance. In this investigation, we made a compromise by conducting measurements on a limited scale to validate an analysis tool for the prediction of propagation effects in urbanized areas. In addition we repeated sensitivity measurements in Burum whereby the frequency band of interest was expanded to also include the 3600-3800 MHz band. As far as 5G systems are concerned, the emission features of 5G base stations relevant in this investigation have been assessed, parameterized and taken into account. Measurements on actual 5G systems have not been conducted. Relevant signal and deployment parameter values were based on literature findings. Our hypotheses on 5G deployment approaches have been validated through private consultation of mobile operators (KPN, Vodafone, T-Mobile and Tele2) after which we shaped these hypotheses into stylized deployment scenarios, which can be interpreted as options of a hypothetical operator and have been used in the impact assessment. In a similar way we have discussed the current and foreseen operational use of the Burum Interception Facility with the Joint Signal Cyber Unit who is responsible for the exploitation of the Burum Interception Facility. The dominance of statistics in this problem and limitations in validation particularly concerning measurements require some caution in the interpretation of the impact prediction.

The inventory and assessment of mitigation solutions both on the mobile communications as well as the interception side are based on a combination of focused desk research, specific inquiries among selected technology/knowledge providers (Ericsson, Nokia, Huawei, SED Canada, Brigham Young University) and the background expertise available at TNO concerning 5G, radar and electronic defense.

TNO consulted the KNMI regarding the predictability of atmospheric conditions which are of influence on long distance propagation in this frequency band.

1.5 Structure of this report

This report is structured as follows. Chapter 2 is a concise chapter on the topic of satellite communications and interception. The most relevant and unclassified aspects related to the Burum Interception Facility are presented. The next chapter is more elaborate and discusses the 5G developments with an emphasis on aspects which are particularly important to this coexistence problem. Chapter 4 introduces a 5G scenario framework which has been used as input of the 5G impact analysis. Chapter 5 is a large chapter and presents the approach and results of the impact analysis as well as the inventory and assessment of possible mitigation measures. These results have been input to an analysis of the perspective on co-existence both on the mid and long term. It also contains proposals for a co-existence arrangement in Chapter 6. Conclusions and recommendations are contained in Chapter 7. Chapter 8 contains the list of abbreviations used in the report. The report also contains a series of annexes on various technical topics and two non-technical annexes. The technical annexes provide justification of the impact assessment approach and intermediate results. The way we handled massive MIMO in this investigation is reported. There is also an elaborate annex discussing alternative interception techniques based on spatial filtering, supported with a mathematical treatment. The last two non-technical annexes respectively contain the academic appreciation of Prof. Baltus and the outcome of the assessment on possible anti-competition elements contained in the report.

2 Characterisation of Burum Interception Facility

2.1 C-Band Satellite communications

2.1.1 Use of C-band in satellite communications

The C-band between 3400 and 4200 MHz is the first band that was used for satellite communications. The original C-band was from 3800 to 4200 MHz but at a later stage the 3400-3800 MHz band was added as extension band. 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 which allow robust communications at low signal levels.

C-band satellite communications is used to provide broadcast services as well as bidirectional and resilient communication links which are relevant in various (professional) application domains and in geographical areas where terrestrial infrastructure is absent or cannot be fully relied on. Specific examples are:
- communication links with the highest availability for the maritime industry, the oil and gas sector and in challenging terrain and remote territories,
- early restoration of vital broadband connectivity in disaster-hit areas[3],
- access to education and health care in developing countries[4],
- communication links to cruise ships.

C-band is also used for feeder (and TT&C) links in mobile satellite communication systems. An example is Inmarsat[5], which has a gateway earth station in Fucino (Italy) as well as in Burum (Netherlands). In this case, the communication between user equipment and the satellite (user link) occurs in L-band and from the satellite it is redirected to the gateway station in the C-band (feeder link). When the communication arrives at the gateway station it can be either routed into a fixed terrestrial network (telephony or internet) or back via the satellite to another mobile satellite communication user[6].

[3] Source: http://www.emergency.lu/
[4] Source: https://satmed.com/
[5] Source: https://www.inmarsat.com/
[6] Source: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=2ahUKEwjRh5mcqbXdAhXIYVAKHRdyD0UQFjABegQICRAC&url=https%3A%2F%2Flicensing.fcc.gov%2Fmyibfs%2Fdownload.do%3Fattachment_key%3D-94644&usg=AOvVaw10fcztakMBx2SrFsxzkBl0

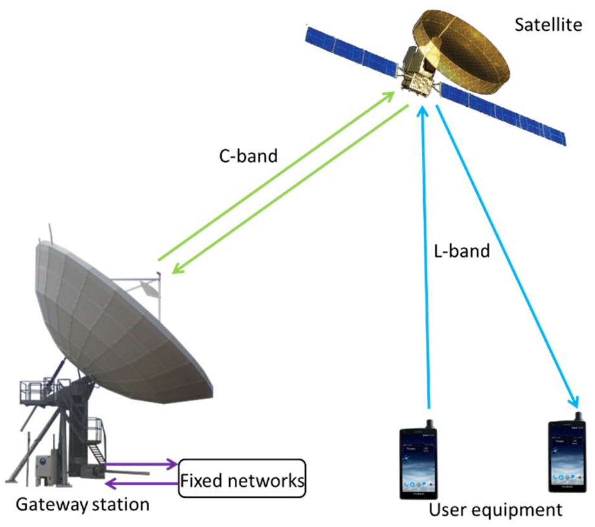

Figure 3.1: Mobile satellite communications system.

2.1.2 Status and future of C-Band communications

Many of the satellite communication systems operating in C-band are not expected to disappear any time soon. Especially in areas where heavy rain occurs often and where a high availability is required, it is very likely that the C-band, due to its characteristics, will remain to be used. This is also confirmed by new satellites providing capacity in C-band are still being launched today.

Considering the future use of the C-band for the feeder links in mobile satellite systems , Inmarsat has recently stated the following[7]:

"Inmarsat's L-band satellites carry safety service traffic as the only operator authorized to do so by the IMO and additionally supported by International Civil Aeronautical Organization as well as key security and critical infrastructure services. They use the 3.5 GHz band for receiving signals from the satellite to its Ground Network. The expected lifetime of these satellites is beyond 2030, with new satellites under development and these bands have already been included and coordinated."

Noting that coordination is a tedious process, the use of the C-band for feeder links in mobile satellite systems is also not expected to change in the near future.

2.1.3 Users and Ground Stations

C-band is not only used commercially, but also for military satellite communications because of its specific features. Mobile satellite communication systems in particular are widely used by government and military users, because they provide reliable communications with small terminals.

[7] Source: https://www.tweedekamer.nl/downloads/document?id=b299e236-b24c-4a5f-856f-f56e366b71d6&title=Position%20paper%20Inmarsat%20Solutions%20BV%20t.b.v.%20hoorzitting%2Frondetafelgesprek%20De%20uitrol%20van%205G%20in%20Nederland%20d.d.%2029%20maart%202018%20.docx

In the Netherlands, main large C-band terminals are located at the military satellite ground station at Lauwersmeer and in Burum where Inmarsat has a gateway station operating in C-band for the feeder links with their L-band satellites and (collocated) the JSCU has its satellite interception ground station operating (among others) in C-band.

Figure 1: Lauwersmeer

Figure 2: Burum

2.1.4 Satellite Ground Station Burum

The wide area coverage provided in C-band enables SGS Burum to intercept signals from C-band satellites positioned over a wide range in the geostationary arc. This also holds for the feeder links (in the C-band) of mobile satellite systems operating in geostationary orbit.

Since C-band satellite communications are used by military around the world and mobile satellite communications enables communications with small low cost equipment in areas without any infrastructure, and therefore can be one of the few or even the only viable option for communication that militant adversaries operating in such areas may have, they can be considered a source of intelligence.

In comparison with other methods of intelligence gathering, the interception of communications through satellites offers a unique way of catching the communication of adversaries and provides a gateway to information on hostile elements, not otherwise accessible through other means.

The importance of the interception facility at SGS Burum (specifically referred to in this report as the Burum Interception Facility) also indicated by the decision of the Dutch government - as a reaction to 9/11 - to extend the satellite interception capacity to counter terrorism[8].
Also, with the ever growing importance of cybersecurity for the nation, the role of C-band interception as an important enabler in the cyber security effort is expected to grow even further.

Intelligence moreover, cannot be purchased easily or without exposing ones key intelligence interests. A self-reliant intelligence position is therefore expected of the Dutch intelligence community by the government. SHF satellite interception, especially in C-band, provides a relative safe and proportional way of dealing with the challenges mentioned above.

Intelligence to counteract terrorism remains important considering that the threat level (Terrorist Threat Assessment Netherlands (DTN), published by the NCTV four times a year[9] is substantial since 22 March 2013, meaning that there is a real risk of a terrorist attack in the Netherlands.

2.2 Satellite Communications Interception

The required intelligence is determined by the areas of interest and depth of investigations which are yearly specified in the “Geïntegreerde Aanwijzing Inlichtingen & Veiligheid (GA I&V)”[10] by the Minister-President, the Minister of Defence and the Minister of Interior and Kingdom Relations, after consultation with the Minister of Foreign Affairs and the Minister of Justice and Security.

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[8] Source: Bestrijding internationaal terrorisme; Brief ministers met 'Actieplan terrorismebestrijding en veiligheid, KST 55923, kenmerk 2295, nr. 10, url: https://www.parlementairemonitor.nl/9353000/1/j9vvij5epmj1ey0/vi3ajy7vxxz0
[9] Source: https://www.nctv.nl/organisatie/ct/dtn/over_dtn/index.aspx
[10] Source: https://wetten.overheid.nl/BWBR0041158/2018-07-17

The areas of interest specified in the GA I&V drives the selection of satellites to be intercepted by SGS Burum. For the satellites making use of the C-band, it may not be known beforehand which part of the frequency band they actually use nor which parts of these frequency band potentially contains the communications which are relevant to be intercepted (i.e. contain intelligence). In addition, SGS Burum has the capability to simultaneous intercept multiple C-band satellites, which each may operate in different parts of the C-band (like the different parts of the C-band which are used for feeder links by different mobile satellite communications systems). For these reasons it will be very difficult for the JSCU to predict the frequency bands which are of high or less high importance to be intercepted.

In future, adversaries may no longer make use of satellite communications in the 3400-3800 MHz band and move to satellite communications provided by satellite systems operating in other frequency bands. Whether and when this move occurs is out of control of the JSCU.

2.2.1 Requirement

The government requires that interception is not affected by the introduction of 5G or any other wireless systems. An interception production loss of 0.0038% is considered to be the limit. This production loss figure refers to technical interception loss which cannot be easily linked to loss of intelligence value as a result of missed interceptions. Any exceedance of this limit will impede the requirement of the government to be met.

2.3 Summary

The interception capability of SGS Burum in the 3400-3800 MHz band is an important source of intelligence for the Netherlands and is expected to remain important for some time. It will also be difficult to replace it by other means.

It should be noted that there are other parties using the C-band which are also of importance to the Netherlands. For instance Inmarsat, providing safety service traffic as the only operator authorized to do so by the IMO as well as key security and critical infrastructure services (used by for instance the Dutch coastguard). The specific requirements of these parties with respect to 5G interference have not been taken into account in this report. This is justifiable because co-existence criteria will be more stringent for the interception application than for satellite communication services.

3 5G based mobile networks

3.1 Introduction

5G[11] or IMT 2020 (International Mobile Telecommunications 2020) according to the ITU is the new fifth generation of wireless cellular networks and is the designated successor of LTE (Long Term Evolution) also known as 4G.

In this chapter we will introduce the topic 5G and focus on aspects which have particular relevance to the matter of co-existence treated in this report. Annex A contains additional information for further reading.

3.2 Relevance of 5G to Dutch society

Our society finds itself in the middle of a digital transformation process which was predominantly induced by technological advances on a global scale in areas of micro-electronics, information technology and telecommunications. This transformation process entails the digitization of systems of any kind and processes in basically every sector of our economy, and can also be felt in almost every aspect in our daily life. This is everything but a top-down transformation due to the widespread availability of advanced but affordable electronic services and applications to all. While in the past, information technology had just a supporting role in professional organizations, it has now become an essential component in fast growing portfolio of products and services in professional and consumer markets. We are quickly transforming into a ‘digital only and fully networked’ society. The Cabinet formulated the Dutch Digitization Strategy[12] which reflects the ambition of the government to maintain a leading position on digitization in Europe especially when it comes to turning state of the art technologies into new innovative applications. Obviously the realization of this ambition also sets the bar for digital infrastructures in this country.

In the targeted digital society, wireless connectivity is a universal capability and wireless networks are considered to be of at least equal importance compared to cabled infrastructure and not just the extension of that. The potential pervasiveness of wireless networks cannot easily be challenged by fixed networks and the conventional shortcomings of wireless in terms of bandwidth, connection availability and delay have been addressed by industry. The design goals for 5G as they were defined by the industry in 2015[13] are targeting the role of a versatile and high performant wireless infrastructure that could meet a wide range of current and expected application specific requirements in various sectors of society, like health care, industry, mobility and last but not least consumers.

[11] 5G is the market brand name for IMT-2020.
[12] Nederlandse digitaliseringsstrategie, Ministerie van Economische Zaken, juni 2018
[13] NGMN White paper on 5G and 5G-PPP Vision paper, both published in 2015

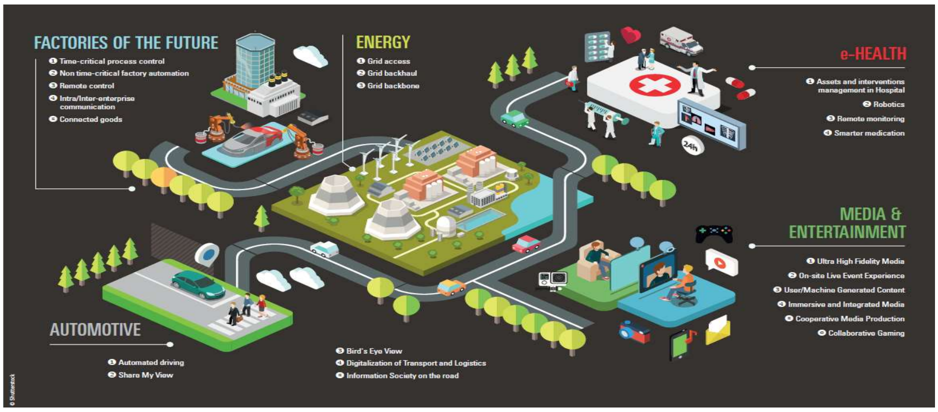
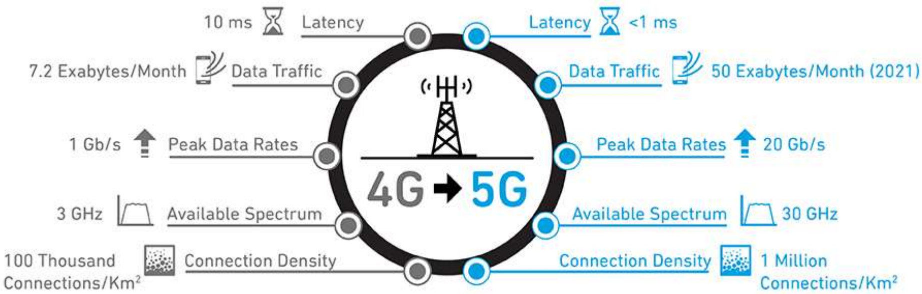


Figure 3: Versatile use of 5G: wireless applications in various sectors in society. Source: 5G-PPP

With the 5G design goals, a clear paradigm shift was made compared to previous generations, including 4G. Where the paradigm shift is clearly visible is in the NGMN vision. 5G should not just be about providing faster mobile Internet access, but more about supporting all kinds of applications. The diagram below illustrates how 5G differs from 4G in various performance aspects.

This promise of great versatility and service performance also explains the international hype around 5G. Although the urgency for 5G technology development comes from Asia where 5G is expected to deliver the connectivity to enable highly advanced services and applications in the multimedia domain and resolve growing capacity issues, the EU considers 5G as pivotal technology for future economic growth and prosperity, particularly emphasizing its role in the digitization of society. The United States of America also embraces 5G but with an emphasis on stimulating nationwide broadband coverage. The EC seems to be most outspoken about the potential of 5G for European society in a wider sense, compared to other regions in the world. It considers 5G as an accelerator in forming a single digital market and as a key component of the future economic development of the EU. It therefore strongly promotes 5G technology development particularly targeting specific sectors. The EC launched in 2016 the 5G Action Plan[14], leveraging the 5G-PPP initiative and comprising a series of actions to speed up 5G development and deployment across the whole of the EU.



[14] Source: European Commission, *5G for Europe; an Action Plan*, COM(2016) 588, September 2016.

Figure 4: Transition from 4G to 5G: an upgrade on various performance aspects. Source: Qorvo.

The Netherlands as an EU member state and with a very open economy has an economic policy agenda that shows clear alignment with corresponding EC policy goals, especially regarding digital transformation[15]. The “Topsector beleid” which promotes a limited set of Netherlands specific technology programs and roadmaps (9) with ICT being essential to them all, explicitly mentions 5G in the knowledge development program as one of the 5 ICT related fields[16].

Another important driver behind 5G is to be able to keep up with the growth of mobile data traffic. Mobile traffic is expected to grow considerably in the coming years. Different, and sometimes biased, forecasts point in the same direction which is the steadiness of the exponential annual growth factor: 1.5-2.1 (2014-2020; worldwide)[17], 1.2-1.4 (2016-2025; NL only)[18], 1.4 (2018-2021; Western Europe/UK)[19]. ACM published figures[20] about mobile data consumption in the Netherlands for the years 2014 until 2017 which indicate an annual growth of even 1.9, which is even considerably higher than the aforementioned forecasts for Western Europe including the Netherlands. We have been reluctant to adopt the 1.9 figure in this analysis without a thorough understanding of this figure and stayed with the annual growth prediction of Cisco VNI of 1.4. According to Cisco VNI, 80% of the mobile traffic in Western Europe in 2021 will be video.

The chart below shows a few growth curves (in logarithmic scale) with 2015 taken as the baseline. The ACM curve is obtained through extrapolation into future years.

[15] Source: Actieplan Digitale Connectiviteit, Ministerie van Economische Zaken, juli 2018.
[16] Source: Kennis- en Innovatie Agenda 2018-2021, December 2017
[17] Source: ARIB, Views on IMT beyond 2020, 2014
[18] Source: Aetha, 2016
[19] Source: Cisco-VNI Mobile traffic forecast 2016-2021
[20] Source: ACM Press Release, May 28th 2018

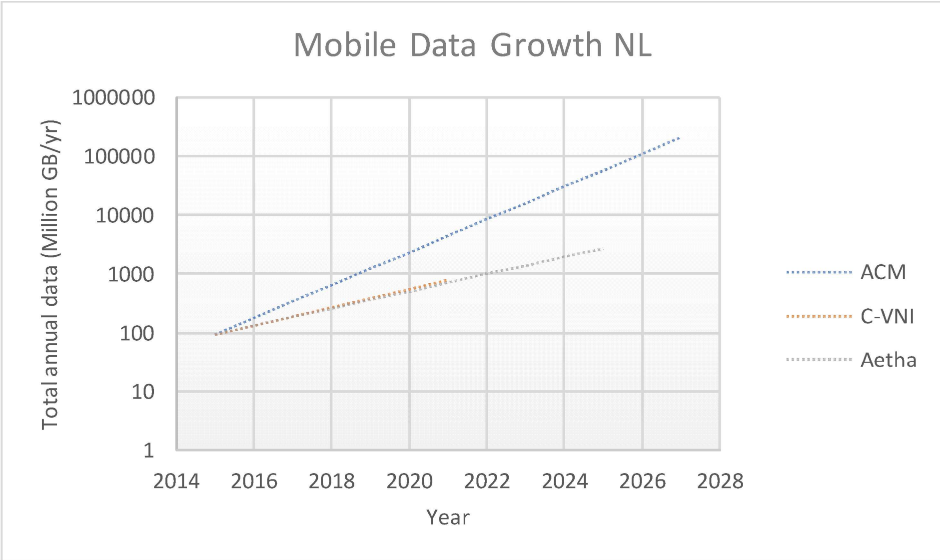


Figure 5: Annual mobile data growth predictions for Western Europe/the Netherlands. Sources: ACM, Cisco VNI, Aetha.

This traffic growth must be absorbed by mobile networks either through technology advances, additional spectrum, densification of sites or combinations of those. New 5G technology (e.g. MIMO) and spectrum should help to keep up with the growth of mobile data traffic in a cost effective way. The Boston Consultancy Group reported on simulation outcomes which indicated that in major Western cities like Berlin, Paris, Milan, the 4G capacity on the existing infrastructure will be fully exhausted by 2021 and a tripling of infrastructure density would be required to keep up with the traffic growth[21].

3.3 Main features of 5G

3.3.1 Service categories identified in 5G

The ambition of 5G as laid down in the 5G recommendations of the ITU is to support the following categories of services[22]:

1) **enhanced Mobile Broadband (eMBB):** mobile Internet type services with high capacity and services with high data speeds to enable for example ultra high definition video (UHD) streaming, video conferencing and virtual reality (VR). The aim here is to reach considerably higher capacity and speeds than possible with 4G systems. The eMBB usage scenario covers a range of cases, including wide-area coverage and hotspot, which have different requirements. For the hotspot case, i.e. for an area with high user density, very high traffic capacity is needed, while the requirement for mobility is low and user data rate is higher than that of wide area coverage. For the wide area coverage case,

[21] Source: Boston Consultancy Group, *A playbook for accelerating 5G in Europe*, September 2018.
[22] See also: see also ITU-R M.2083

seamless coverage and medium to high mobility are desired, with much improved user data rate compared to existing data rates. However the data rate requirement may be relaxed compared to hotspot.

2) **Ultra-Reliable and Low Latency Communication (uRLLC):** this relates to wireless connections with high Quality of Service performance in terms of latency, reliability and availability. Examples include wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, transportation safety, etc.

3) **massive Machine Type Communication (mMTC)**: mMTC aims to provide improved coverage and service to extremely high numbers of connected devices per square meter. This clearly relates to the Internet of Things development, targeting small devices with low battery power consumption that need a wireless connection to the cloud. The spectrum of application areas is broad (smart cities, smart buildings, etc.). Data speeds in such applications are typically much lower than average. It turns out that the 5G requirements for mMTC can already be achieved with the NB-IoT and LTE-M radio interface technologies. There is no 5G specific new mMTC radio interface, basically the same IoT optimized radio interface as for 4G are used with similar network enhancements.

The introduction of new services and the introduction of the uRLLC service category may induce a higher acceleration in capacity requirements in the long term compared to what is observed today. This is very difficult to quantify now as it will depend on how successful applications will become that make use of these service types. If we take the multimedia application domain, social VR is a new application in which people can meet and see each other live in a fully virtual 3D environment. Such applications are even with clever compression techniques very bandwidth and latency demanding and can quickly result in substantial traffic growth if they become mainstream. Another example is automated driving on highways. This may take another five to 10 years but once it reaches the mass market it will very seriously influence connectivity needs along highways. Not only will vehicles themselves require almost permanent connectivity to (local) cloud services but the consumption of streaming content in vehicles may increase substantially.

Not only the data bandwidth of services determines the required capacity in 5G. In uRLLC services also other QoS performance metrics influence the amount of (radio) resources that is needed. A service with low latency needs more radio resources than a service with similar throughput but without low latency requirements. With low latency, some of the normal error correction procedures cannot be used. Therefore a higher link budget, or less coding efficiency is needed to still get the required reliability. This implies that less connections can be provided via the same base station in the same frequency band. Similarly, high data reliability (no packet loss) has an impact on the required amount of radio resources.

A study on the implications of a 5G roll out investigated, for a range of different sectors, which type of advanced applications could emerge that would depend on certain 5G key capabilities (low latency, service level guarantees, device density, low power use, peak bandwidth). These example applications are listed below[23]:

[23] Source: DotEcon and Axon, Study on implications of 5G deployment on future business models, BEREC/2017/02/NP3

Table 1: Overview of sector specific application examples, aligned with different 5G connectivity features. Source: dotEcon and Axon

	Automo-tive	Media and enterta-inment	Manu-facturing	Logistics	Agricul-ture	Energy and utilities	Health-care	Other verticals
Low latency	Safety applications	AR/VR Off-site media production	AR/VR Critical M2M communicat ion/safety	Drones	Drones		Wireless Telesurgery	Real time control applications
SLGs / reserved capacity	Safety applications	Content distribution	Critical M2M communicat ion/safety	Drones	Drones	Smart grids	Wireless Telesurgery	Safety applications Public safety
Device Density		Stadium/ events	Sensor networks/ M2M		Sensor networks/ M2M		Asset tracking	Dense sensor networks for M2M or IoT
Low power use			Sensor networks/ M2M	IoT tracking	Sensor networks		Smart wearables	Dense sensor networks for M2M or IoT
Peak bandwidth	Live video for 'see through the front' vehicle	Immersive media such as AR/VR 360 video	AR/VR				Wireless telesurgery	

This table will not be treated in detail here but the mentioning of drone applications triggers the remark that the use of this and other types of airborne applications using C-band spectrum induces a more severe co-existence issue.

The eMBB category of use cases is best understood and generally believed to be the most prominent in terms of market appeal and adoption during the first years of 5G network exploitation and is supposed to drive the 5G roll out[24]. It is expected to have a strong appeal in the consumer market which is the main market segment for MNOs nowadays. At the same time, it is doubtful that consumers are willing to pay more for mobile communications, even if they get higher bitrates and larger data bundles. It is not so clear whether consumers may be willing to pay for new advanced services (e.g. VR) that are not available to them now[10,17].

The uRLLC service category is important for advanced and latency critical bidirectional/interactive multimedia applications, but also reaches out to professional markets (different verticals such as mobility, smart industry but also public safety). In these markets confidence needs to be built that business/mission critical communications can be handled by mobile operator networks with the required performance. We do already see local area business critical applications, which could be seen as a forerunner development.

The mMTC proposition addresses the 'Internet of Everything' era in which IoT has become fully ubiquitous. In hindsight, IoT has taken off more slowly than was expected which is for a large part due to standardisation struggles. Right now both proprietary as well as 3GPP standardized solutions have entered the market which

[24] Source: dotEcon and Axon, Study on implications of 5G deployment on future business models, BEREC/2017/02/NP3.

will mutually compete in addressing the growing demand in this field in the coming years. This development makes it less clear when mMTC will really kick in.

In conclusion, it is expected that the market adoption of genuine 5G-uRLLC and 5G-mMTC based applications might take more time compared to eMBB.

3.3.2 5G for residential access

A well known application since the nineties is Fixed Wireless Access (FWA)[25] for which the 3.5GHz band and 26 GHz were the originally targeted frequency bands. With new 5G radio technology and the latest antenna technologies, FWA seems to enter a period of revival as an alternative solution for Broadband Access, particularly in rural areas as well as in areas where it can compete with DSL and/or Cable based service propositions. In the USA, FWA is actually the front runner use case for 5G. FWA is clearly in scope of industry and telecom operators.

An alternative for residential access may be access solutions, where access for homes and the devices in the homes is provided with a combination of fixed access and mobile access. With the increase of flat fee subscriptions, we can even see that mobile devices use cellular access even when WiFi via fixed access is available.

[25] At the time also known as Wireless Local Loop (WLL)

3.3.3 *New Radio (NR) as new workhorse*

Apart from commercial perspectives, probably the most important driver for operators to change technology is a reduction of costs per bit which is an essential target for operators in the light of the exponential growth in traffic demand.

The new workhorse to achieve the 5G ambitions and to provide this cost reduction is the New Radio (NR) standard. NR provides a completely new radio interface specification which is not backwards compatible with that of LTE. In terms of performance, NR provides a much stronger performance growth potential compared to LTE (4G) and its evolution, as depicted below. Industry claims a strong reduction in average cost per bit with the transition to NR[26], which is essential to maintain a sustainable valid business case in the light of strongly growing traffic demands. Relevant technical aspects of NR will be treated elsewhere in this report.

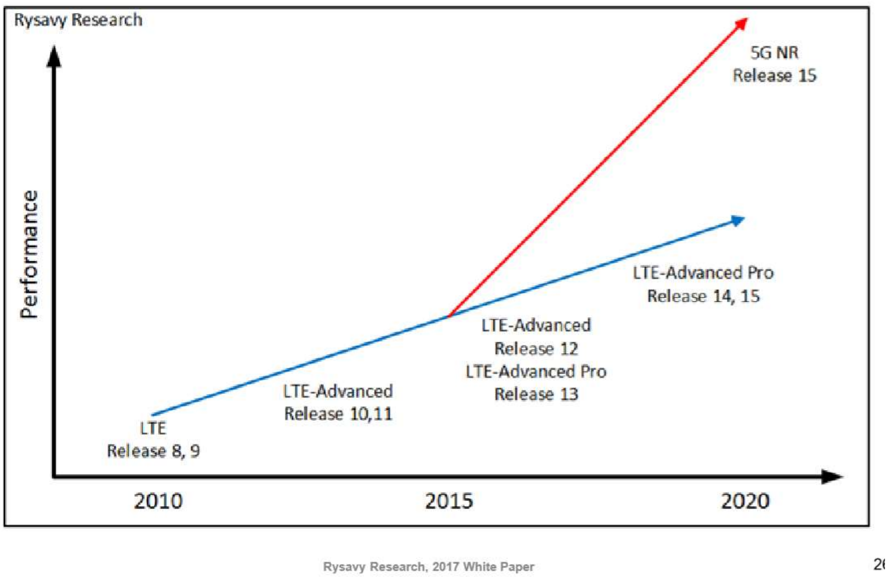


Figure 6: Holistic view of system Performance of LTE and NR technologies. Source Rysavy Research[27]

As a matter of fact the spectrum efficiency gain of NR technology over LTE as such is not very substantial. NR however is designed such that it would have a perfect fit with the use of massive MIMO antenna technology, a technology which allows spatial reuse of the same frequencies, and which has been already introduced in LTE. It is this combination that provides the outlook towards large to very large spectrum efficiency gains, depending on the band in which it is applied. Additionally, the energy consumption per bit has decreased compared to LTE which reduces operational exploitation costs.

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[26] Source: Ericsson, *5G Deployment considerations*, white paper

[27] Source: Rysavy Research, *LTE to 5G: Cellular and Broadband Innovation,* white paper, 2017

The 5G radio interface is suitable over a very wide frequency range (450 MHz to 52.6 GHz) in order to move away further from frequency band dependent solutions we have until today. The availability of new large contiguous frequency bands that 5G can address also brings down the cost per bit. 5G based networks also have an unprecedented level of system flexibility and reconfigurability so it can adapt easily, smartly and rapidly when demand, conditions or functional requirements change.

3.3.4 Technology availability

Industry will have standardized 5G infrastructure solutions available in 2019 covering all three so called *pioneer bands* with the 3.5 GHz band being the prioritized band (suppliers differ in their preferences)[28]. It may be that the first wave of systems has to be configured either for the 3GPP-LTE band 42 (3400-3600 MHz) or band 43 (3600-3800 MHz) band but this distinction, if applicable, is expected to disappear in subsequent waves. So, systems can be configured for any subband within a tuning range between 3300 and 3800 MHz (n78 band according to 3GPP nomenclature[29]). Bandwidths supported in the n78 band are 20 MHz, 40 MHz, 50 MHz, 80 MHz and 100 MHz.

5G NR technology will also become available in other frequency bands but the timing will depend on how the market demand for 5G in other bands will develop. Given the fact that NR technology as such offers limited improvement over spectrum efficiency (10-20%) over LTE, the incentive for operators to switch quickly to NR technology in other (lower) bands may not be strong.

Massive MIMO antenna technology already exists; a 64T64R system reflects the current state of the art for operational systems, while in-lab experiment with 256T256R configurations are taking place. In the coming time, operators will need to gain experience with this technology through trials.

In 2020 or even earlier, mobile handsets as well as CPE equipment will be offered in the market that support 5G NR.

Hence, early In the 2020-2025 time frame this ecosystem will have been fully developed, at least for the pioneer bands.

3.3.5 Example deployment: Elisa network in Tampere, Finland

At this point it is illustrative to describe the Elisa network deployed in Tampere Finland, and which is claimed to be the very first commercial 5G network in the world. We will treat aspects of this example deployment also later in this report. The source is Rewheel[30] who are not entirely unbiased towards 5G application in the 3.5 GHz band, but their brief report[31] about Elisa seemed to provide an objective look on the performance of 5G in this band and the performance of Elisa in particular.

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[28] These frequency bands are treated in detail in section 3.4.
[29] Source: TS 38.101, 3GPP
[30] Rewheel is a Finish management consultancy bureau, specialized in mobile telecommunications. See www.rewheel.fi
[31] Source: https://www.linkedin.com/pulse/first-impressions-from-worlds-commercial-5g-network-pal-zarandy/

The Elisa network consists of three base stations deployed in the Tampere city area and operated by Talinn Estonia to provide commercial services since June this year. The TDD based network is manufactured by Huawei and is equipped with Adaptive Array Antennas (64T64R) which allow beamforming. The base stations are relatively far away from each other so contiguous coverage is not yet feasible. The user terminal used during the assessment had a temporary bandwidth restriction so only half of the typical channel bandwidth of 100 MHz was used. The transmission power is set to 40 Watts (200 W is maximum). Indoor as well as outdoor performance assessments were done. Outdoor, a steady throughput was measured of 360 Mbit/s. Indoor, this was reduced to 250-300 Mbit/s.

Figure 7: Elisa: first commercial 5G network, deployed in Tampere, Finland. Source: Rewheel.

3.4 Preference of C-Band for 5G

There is a great interest in the use of the C band (including 3.400-3.800 MHz) for 5G mobile communications, for which the motivation may not be immediately clear. This aspect is discussed here, whereby a broader view is taken on the spectrum matter to put the C-band discussion in the proper context.

3.4.1 Spectrum is fuel to mobile networks

What radio spectrum means to mobile networks is like what fuel is to cars and air to living creatures. Any mobile communication network cannot operate without frequencies. The volume of spectrum needed by a mobile network depends on a lot of factors but simply stated, it grows proportionally with the amount of traffic the network must handle and it is inversely proportional to the density of base stations and corresponding antenna sites in the network. The exponential growth of mobile traffic demand that is observed in the past and continues for some time to come must be coped with either through: acquiring additional spectrum, use of more spectrum efficient technologies or through site densification. The scarcity of spectrum as a natural resource and the cost (and burden) of infrastructure deployment and of technology upgrades establishes the relative economic value of radio spectrum. The value of spectrum to the mobile operator is not band agnostic. *Low band spectrum* (< 1 GHz) is most limited in volume (most scarce) and is ideal to cover wide outdoor areas and to provide indoor coverage due to its physical propagation characteristics. It is much less suitable to support high data speeds and high capacity because of the limited bandwidth of frequency bands in this part of the spectrum. *High band spectrum* (24-40 GHz) offers the complete opposite; large volumes of spectrum (no scarcity), very limited coverage area, but very high data speeds. *Mid band spectrum* (1-6 GHz) offers a compromise between both extremes.

For over a decade now, the national regulator applies the technology neutrality principle to frequency bands, meaning that any wireless technology can be applied in a band which is designated to mobile communication services, as long as essential requirements are being met. Hence, there is no regulatory preference, let alone requirement to apply 5G in any specific band. Industry however has a very strong influence on the mapping of technologies on to frequency bands. Although for industry also the ultimate goal is that mobile devices and network equipment can support any of the available frequency bands, the reality is that especially in early implementations, mobile devices and network equipment will only support specific frequency bands. Some level of harmonisation is needed to ensure that mobile devices and network in the different regions of the world will be able to work in compatible frequency bands.

3.4.2 *5G Pioneer bands*

The term *Pioneer* bands is brought by the EC. The previously mentioned EU 5G Action Plan[14] mentions the 700 MHz band and also points at the 3.6GHz band as possible/preferred bands to accommodate the introduction of 5G. The Radio Spectrum Policy Group (RSPG) acknowledged these indications and specifically recommended the 3.6 GHz band to be the primary band for the introduction of 5G[32]. The diagram below shows how this European designation fits into the international spectrum plan.

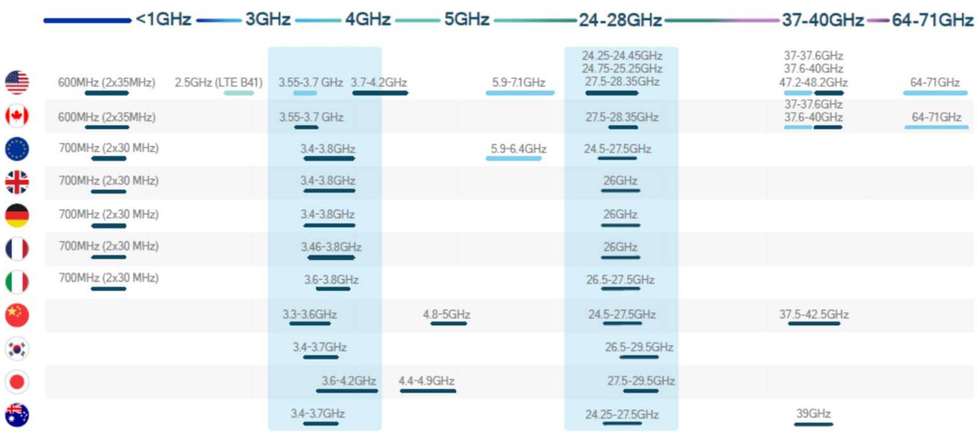

Figure 8: Designated new bands for 5G for various parts of the world. Dark blue bars represent licensed spectrum; light blue refers to unlicensed/shared; green refers to existing bands. Source: Qualcomm.

[32] Source: RSPG: Strategic Roadmap towards 5G for Europe, Opinion on spectrum related aspects for next generation wireless systems, RPSG16-32, 9 November 2016.

The 700 MHz band is considered to be a pioneer band mainly to bring (5G based) mobile broadband to rural areas.

The *second* pioneer band is the 3400-3800 MHz band which is a large part of what is known in the satellite communications world as the C-band which goes up to 4200 MHz (left blue colored column). The 3400-3800 MHz band is often considered as the combination of two parts i.e. 3400-3600 and 3600-3800 MHz due to differences in existing spectrum assignments. The diagram above indicates differences in the precise allocation of C-band spectrum for mobile communications depending on regional/national differences in spectrum plans and usage. Europe chose to harmonize the 3400-3800 MHz band for fixed, nomadic and mobile communications services and has requested member states to make this spectrum band available on a national level based on market demand, taking into account protection of existing services such as Fixed Satellite Services[33]. The EC considers this band as the *primary* pioneer band for the introduction of 5G. Actually, the whole 3400-4200 MHz band has been under consideration by the ITU for IMT. The still intensive and continued use of C-band satellite services in various countries in the world complicates reaching true global harmonization. Hence, the prospects of the additional 3800-4200 MHz part are not quite clear.

Regarding the use of 3400-3800 MHz for mobile broadband services in Europe, member states are not mutually synchronized and show individual preferences regarding making spectrum available for mobile broadband within this band[34]. In the Netherlands according to the national frequency planning (since 2014), the lower band is currently accessible to mobile communication applications which comply with the HOL-008 regulation (until 2026). The same applies to the upper band but with different license expiration dates (2022/2026).

The *third* pioneer band is the 24-28 GHz frequency band (right blue colored column) shows a similar differentiation internationally, but harmonization of this high frequency band is easier compared to C-band. Europe aims at harmonization of the 24.25-27.5 GHz pioneer band before 2020.

The first 5G deployments depend quite strongly on the availability of these new bands in the country of deployment, but eventually 5G technology will become available in various legacy bands.

3.4.3 Why the C-band is considered the most important pioneer band

For the specific pioneer bands 700 MHz, 3400-3800 MHz and 26 GHz, the picture below indicates the favorable deployment choices for these bands. The so called mid bands provide a compromise between these two extremes.

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[33] Source: Commission Implementing Decision C(2014) 2798, May 2nd, 2014.
[34] Source: GSA 5G Report, July 2018

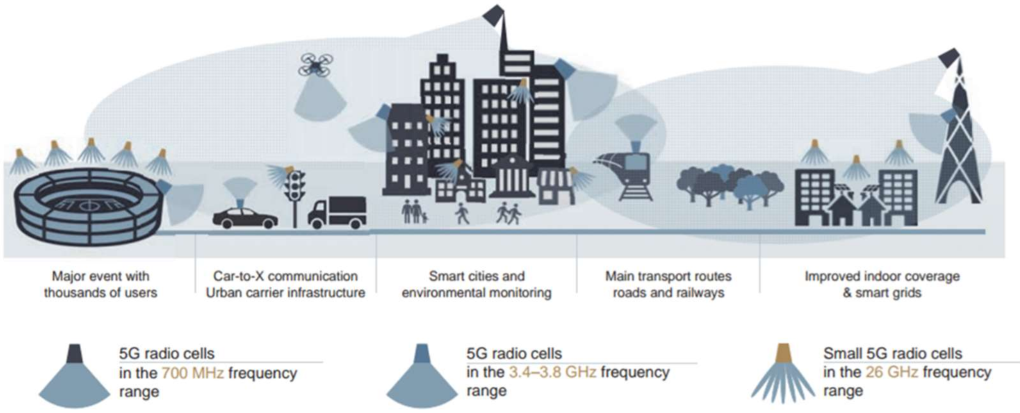

Figure 9: Figure shows foreseen deployment choices for each of the three Pioneer bands. Source: BMVI[35].

The illustration above shows that the use of 3400-3800 MHz base stations is typically foreseen in suburban and urban deployments. The preference for urbanized areas obviously does not preclude the use of 3400-3800 MHz in more open areas. This depends entirely on service as well as capacity demands in those areas.

We will discuss below the relevance of the 3400-3800 MHz band in the context of 5G.

The attractiveness of the 3400-3800 MHz band as such firstly comes from the fact that it offers a much larger chunk of contiguous spectrum. The large size of the band has two advantages. Firstly, very high peak rates can be achieved without having to perform aggregation of carriers taken from other bands. Carrier aggregation is a powerful technique but is also complex and relatively expensive. Secondly, a portion of this size ensures an operator that the expected growth in capacity demand can be absorbed without having to densify the network very soon after the introduction of 5G. BCG reports that with 3.5 GHz spectrum available, densification could be delayed until approximately 2025[17]. Both advantages are important for eMBB based 5G services which are generally considered to offer the quickest commercial potential during the first years of 5G exploitation and will strongly drive the traffic capacity demand. The NR technology exploits this band feature, as it supports a channel bandwidth up to a 100 MHz. An additional benefit is that consequently the occurrence of multiple guard bands, which exist in case of LTE (at 20 MHz channel size), are avoided.

Secondly, the combination of massive MIMO and the Time Division Duplex (TDD) arrangement also works out well because the beamforming capabilities of massive MIMO under practical conditions appear to be more robust in a TDD rather than an

[35] Source: BMVI: *5G Strategy for Germany*, July 2017. This has been used in our 5G scenario framework to assume a small growth figure of the macro network in the presence of a C-band based 5G layer.

in an FDD arrangement[36]. This makes this band a better candidate than many other FDD bands.

Thirdly, and again related to massive MIMO, is the fact that in this band massive MIMO offers an adequate ‘repair’ of the link budget. Due to the propagation characteristics at 3.5 GHz, the link budget would otherwise have been reduced compared to links in lower bands. Below, a diagram is depicted which shows the difference in coupling loss in a comparison between a NR link at 3.5 GHz and an LTE link at 1800 MHz in an outdoor setting. The difference between both links is only about 5-6 dB (higher for NR compared to LTE) which is partly due to the application of massive MIMO antenna technology. It compensates to a certain extent the reduction in physical propagation loss when going to a higher frequency band. The measurement illustrated here is done at the Elisa network but aligns with other publications[37]. Hence, the existing macro network in a city could be reused, especially when the more critical uplink (from mobile terminal to the network) can be handled via a lower band such as the 1800 MHz band.

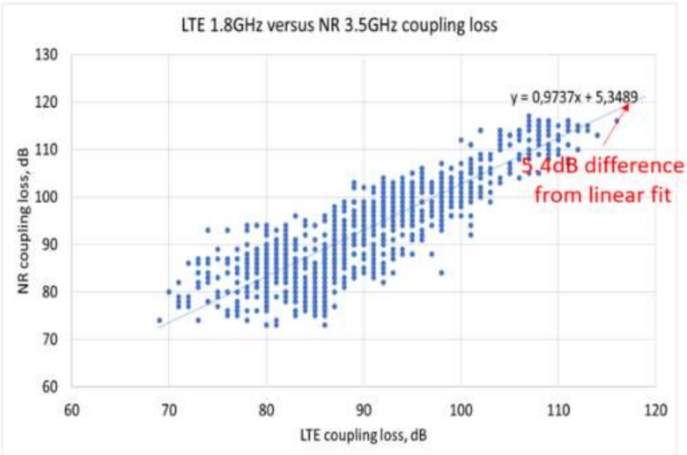

Figure 10: Difference in coupling loss between LTE-1800 and NR-3500 links. Source: Rewheel/Elisa.

Going lower in frequency would alleviate the link budget reduction problem in the first place but massive MIMO antennas at lower frequencies become bigger in size and weight and may introduce installation limitations. Going higher in frequency, the beamforming capabilities improve and antenna weight and size reduce but these higher bands (26 GHz and higher) introduce other challenges which need to be overcome. The grid compatibility advantage does for example not apply to the higher 24-28 GHz pioneer band.

The proper combination of coverage and capacity is very relevant to operators, who often already have a radio network constellation that is designed for lower frequency bands. The wide RF channel is combined with the improved spectrum efficiency of NR-technology, the spatial reuse of frequencies, capability of massive

[36] Source: J. Flordelis et al, *Massive MIMO performance: TDD versus FDD; what do measurements say?,* April 2017
[37] Sources: https://www.telecomasia.net/content/5g-nr-technology-significantly-improves-coverage,

MIMO technology, and the improved radio range also facilitated by massive MIMO through its beamforming capabilities. In conclusion the combination of NR, massive MIMO antenna technology and this particular frequency band is seen by operators as the magic triangle.

Finally, we will discuss the merits of the two alternative pioneer bands.

The 700 MHz band is also considered a pioneer band in the low band region but the proposition of this band is entirely different. It provides very good propagation characteristics also allowing good indoor coverage, meaning that a nationwide 5G network can be set up with a relatively small number of sites. The major disadvantage of this band is the small band available (2x30 MHz). This has to be subdivided among multiple licensees. This means that this band is mainly suitable for low bandwidth services (which can be of a low latency, high reliability nature). The band is ideal for IoT type applications, but is not suitable for eMBB.

The second alternative is the 24-28 GHz band which offers large quantities of bandwidth which makes this band ideal for eMBB type services. However, the band has the drawback of limited service coverage areas. A very suitable deployment option for this band are small cells and the use in Fixed Wireless Access applications. Small cells are often depicted as an important ingredient in future mobile network deployments, but reality is that the application of small cells is challenging in terms of requirements (e.g. power and backhaul connection), subsequent costs and realization timelines. The Small Cells Forum also recognizes current complexities in technology standardization as a delaying factor[38]. Small cells will become more mainstream, but only after the possibilities with the current, predominantly Macro oriented network are exhausted.

3.4.4 *Current spectrum situation for electronic communication services in the Netherlands*

The table below presents the current spectrum holdings among KPN, Vodafone, T-Mobile and Tele2.

Table 2: Current spectrum holdings of mobile operators in the Netherlands

Band	KPN	VF	TM	T2
800 MHz	2x10 MHz	2x10 MHz		2x10 MHz
900 MHz	2x10 MHz	2x10 MHz	2x15 MHz	
1800 MHz	2x20 MHz	2x20 MHz	2x30 MHz	
2100 MHz	2x19.8 MHz	2x19.6 MHz	2x20 MHz	
2600 MHz	2x10 MHz	2x30 MHz	2x5 MHz	2x20 MHz
2600 MHz (unpaired)	1x30 MHz			1x5 MHz

From this table it is clear that KPN and Vodafone have spectrum assets in all bands, which is not the case for T-Mobile and certainly not for Tele2. If the merger between the latter two operators becomes reality, then in 2019, the three remaining operators have approximately comparable spectrum portfolios. A spectrum auction will likely be held end 2019 which introduces for any of the three the risk of losing their 2100 MHz license which in such case would mean that the dependency on the other bands, and particularly the 2600 MHz band becomes larger, for capacity

[38] Source: *Network densification in the 5G era*, Small Cells Forum.

expansion. The 1400 MHz band, to be auctioned at the same time, may be acquired to compensate but this band is smaller and can only be used for the downlink. With a back-of-an envelope calculation it can be predicted that even with the maximum amount of spectrum that an individual national operator would have acquired in 2019, with the technology upgrade possibilities and the typical size of a nationwide Macro network, the expected capacity demand cannot be handled very long without the need for drastic densification of that network.

The table below illustrates the list of spectrum bands which are or will become available for carrier grade electronic communication services in the Netherlands[39]. The table reveals the attractiveness of the 3.5 GHz band to operators due to its relatively large size. The other bands in the midband segment coming available in 2020 are (taken together) considerably smaller and are different in arrangements availabilities.

Table 3: Overview of additional spectrum volumes planned for the Dutch market

Band	Spectrum volume	Next milestone
700 MHz	2 x 30 MHz	2019
800 MHz	2 x 30 MHz	2030
900 MHz	2 x 39 MHz	2030
1400 MHz	1 x 40 MHz (DL)	2019
1800 MHz	2 x 70 MHz	2030
2100 MHz	2 x 60 MHz	2021
2600 MHz	2 x 65 MHz 1 x 55 MHz (TDD)	2030
3500 MHz	1 x 400 MHz (max)	2022 (TBD)
26 GHz	3 GHz	TBD

In the next section, the capacity aspect comes back in the discussion of 5G deployment expectations.

3.5 5G Deployment expectations

The future will not prescribe just one single 5G deployment scenario like this could be done with early generations of mobile communications. Many more factors are involved which lead to different possible outcomes. Mobile operators themselves are just about to step into very coarse business planning with still various open questions regarding market pull, needed investments and their return and last but not least the regulatory conditions (spectrum). We can therefore only postulate some possible and fairly likely deployment options, trusting that reality will not be entirely deviate from those options. Predicting the evolution of 5G networks in the long run is too difficult because nobody knows how demand and supply in mobile services will influence each other over time.

This section will provide some typical rationales on mobile network exploitation which play a role for operators. From those, we derive a set of scenario's which have a certain likeliness to be a launching scenario or which could emerge at a later

[39] Source: Dutch Ministry of Economic Affairs

point in an evolutionary fashion. The time frame which we dare to oversee without too much speculation is until 2030.

Incumbent, nationally operating commercial mobile operators focus their exploitation plans in the direction in which proper returns on their investments can be expected without putting their current business at risk. So business continuity is a key factor. Nationwide 5G service coverage will be established, sooner or later as is currently the case with 4G. Industry facilitates a smooth long term transition from the fourth to the fifth technology generation and to make choices how to prioritize demographically or geographically, and in which frequency bands.

5G technology creates opportunities also for other players, e.g. from outside the telecom space, to get engaged into 5G services because 5G is able to support a much wider variety of business models from what we know today. This is driven by how the market for connectivity services, technical solutions and the regulatory environment all will evolve. Examples of those models which were studied in 2016[40] are :

- **Mega MVNOs**: In this scenario overarching MVNOs are established which corral services from a range of suppliers (including, potentially, traditional mobile networks, WiFi providers, IoT service providers and others) to deliver tailored packages to their end users which utilize the most appropriate supplier to meet the end users’ needs.
- **Self Organising Networks**: In this scenario, the technology of 5G is designed in such a way (primarily in the higher frequency bands) that it does not require specific frequency planning, but so that each cell site selects the optimum frequency from those available to it, and the network self-organizes and self-optimizes the use of spectrum as it grows.
- **Infrastructure Economics**: In this scenario, the cost of providing the cell sites necessary for the expected densification of mobile networks is not commercially viable, and therefore sharing of sites, and of the RAN, is the only way to provide cost-effective services in many areas.
- **Vertically driven**: In this scenario, enhanced 4G networks satisfy the vast majority of user demand, and it is therefore the industry verticals (e.g. transport, healthcare, construction) that are the primary drivers for the roll-out of 5G.

How 5G exploitation will develop over time is not yet clear. Whether 5G will be exploited in the traditional model of nationwide mobile operators or whether these alternative models or combinations of those may emerge sooner or later, will have to be seen. A key assumption we have adopted in this study is that telecommunication operator as mobile connectivity service providers will remain focused on acquiring national carrier grade licenses, alongside other players who either take a role as MVNO (taking wholesale services from national operators) or deploy 5G technology using leased spectrum or license free spectrum. Particularly, industry verticals see an opportunity to take a role of Communication Service Provider themselves to set up 3GPP compatible mobile broadband networks on their own premises using license free or leased spectrum.

[40] Source: LS Telcom, *Study on Spectrum Assignment in the European Union, to support 5G roll out*, SMART 2016/0019

In the literature, pleads or expectations can be found about the deployment of 5G in the 3.5 GHz band in urban areas and along important corridors[41]. This makes sense because commercial operators are inherently sensitive to demographic coverage. Particularly in (crowded) urban environments as well as along transport routes, the C-band features can be optimally exploited with a very good compromise between coverage and capacity, and the demand for mobile services is known to be the highest in such areas which secures the business case. A‘ city only’ presence with 5G is a realistic option mainly during the first years of 5G roll out.

The geographical 3.5 GHz footprint *can* be larger or will grow larger as the demand for advanced mobile services is expected to increase also outside the urban areas. Moreover, a national operator offering mobile services to his subscribers does care about geographical coverage too, to ensure continuity of mobile services. The arrival of entirely new use cases which is expected with 5G could seriously influence the geographic traffic demand patterns in the long run. Many of the new use cases (e.g. public safety, energy, healthcare) require a nationwide geographic coverage. However, this broadening of the business model is expected to take time as explained earlier in this chapter.

The expected build up time of a 5G based nationwide network is approximately two years which is comparable to LTE, but other more gradual build up approaches can be followed if the operator so desires.

Operators can increase their network capacity through technology upgrades which offer higher spectral efficiencies, through additional spectrum and through further densification of the network. An operator’s macro-cellular network consisting of high sites is the workhorse in terms of providing coverage and capacity. The constellation of macro sites form a very valuable asset to operators which they typically want to exploit to the maximum level before turning towards acquiring additional sites, a process which is becoming harder and harder[17,42]. So, a “brownfield” spectrum integration strategy whereby with the new frequencies (700 MHz, 1400 MHz and 3400-3600 MHz) additional capacity layers are added to the already existing coverage layer on 4G, is generally preferred given the speed and marginal costs involved. At the point where according to network planning principles the macro network is fully utilized with the latest technology, densification becomes inevitable. This was in the Stratix study the motivation to consider also an (additional) greenfield strategy comprising the deployment of small cells in the 3600-3800 MHz frequency band. Choosing the upper band for the small cells (while the macro layer uses the lower band 3400-3600 MHz) leverages the availability of this equipment in the European market and also simplifies frequency planning. In the context of this co-existence problem we did not adopt this arrangement in our scenarios because it presumes distinction in relevance between the lower and upper band to the JSCU, which is not the case.

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[41] Sources: BMVI, Nokia, EC

[42] Source: Stratix & ITRC: *Onderzoek naar de kosten van 5G uitrol*, April 2018

4 Framework of 5G Mobile network scenarios

4.1 Defined 5G deployment scenarios

For the sake of this investigation we have introduced a hypothetical operator who intends to create an additional 5G-NR layer on his national macro network in the Netherlands, with 100 MHz available in the 3400-3800 MHz band. This operator has a fixed spectrum portion of 100 MHz available which is in accordance with CEPT recommendations[43]. Our operator can have different ambitions and consider different roll-out strategies to achieve a certain ambition. We defined a framework containing various choices (options) as well as evolutionary steps in time. The corresponding diagram is depicted in Figure 11.

Based on desk research as reported in the previous chapter and based on insights TNO received in the current perceptions on 5G in the Dutch market through private consultations, the following deployment scenarios involving 3400-3800 MHz spectrum have been drafted[44]. 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 (see also section 3.5), 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.

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[43] See also CEPT Report 67, July 6th, 2018.
[44] 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.

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[45], but then scaled back (per Postcode-4 area) to a grid which is representative for our single hypothetical operator[46]. 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[47] 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;

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

[46] We have not used actual site locations in our simulations but rather site densities per postcode area (PC-4). Why this procedure is followed is explained in the next chapter on impact assessment.

[47] 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.

- 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.

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 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.

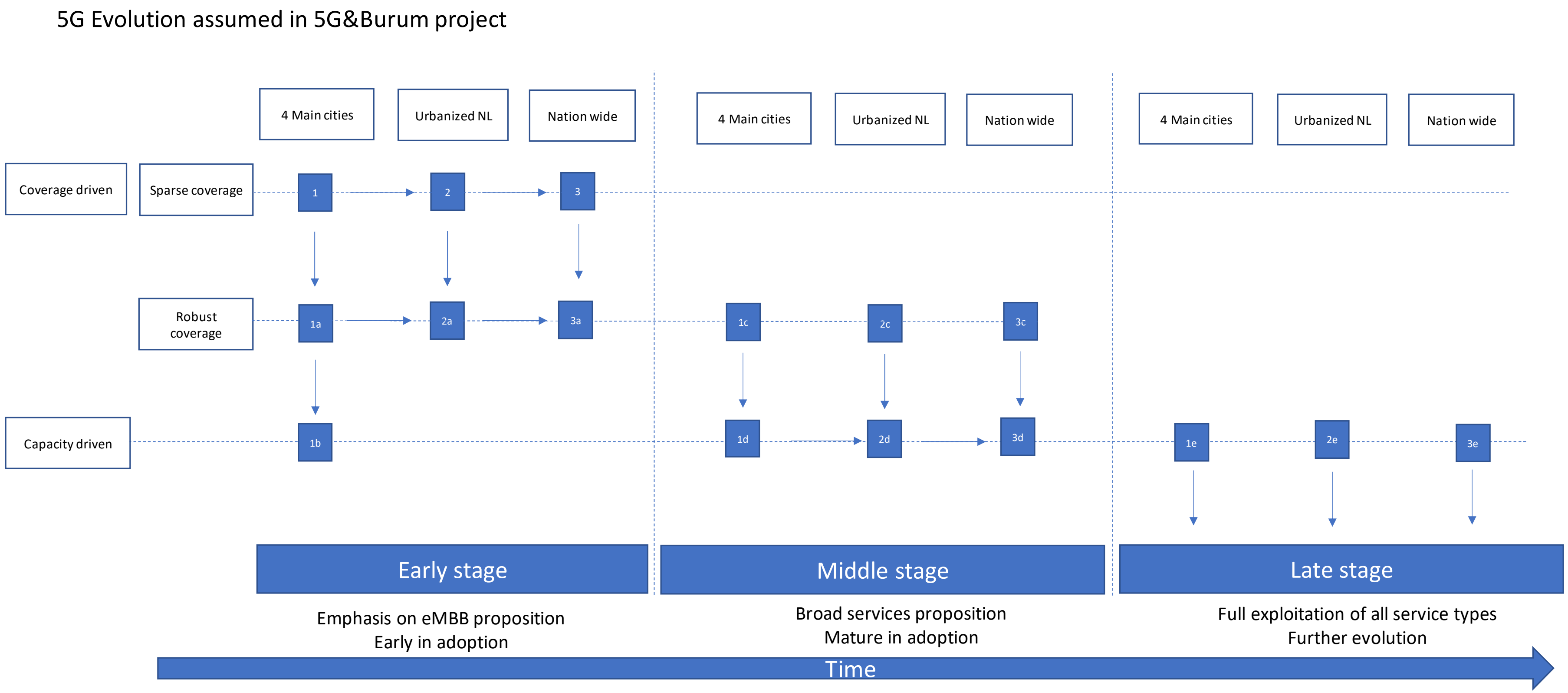

Figure 11: Possible network evolutions and network instances, during three successive stages

The table below contains the 16 scenario profiles. The commonality in geographical scope has been visualized using a colour scheme. Annex C contains a more complete specification of these scenarios.

Table 4 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 radio decoupling target in the 5G-Burum co-existence case, as will be explained later in this report.

4.1.1 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 5: 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[48]) 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[49]. 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.

[48] 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.
[49] 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.

5 Co-existence Burum Interception Facility with future 5G networks

5.1 Approaching the co-existence problem

5.1.1 Goal of the investigation

The investigation should provide clarity to decision makers and other stakeholders concerned regarding the possible impact of the future deployment of 5G mobile networks in the Netherlands, on the performance of the Burum Interception Facility. Also vice versa: what does the existence of the Burum Interception Facility with a given performance target mean for the roll out possibilities and limitations of future 5G networks.

The roles and interests of the stakeholders are clearly different. The government has two different policy responsibilities which are opposing in this particular case: societal security policy which requires also instruments like Burum versus telecommunication market policy and digital connectivity stimulation policies. The telecom operators are players in that market, have commercial objectives and are facing investment decisions on technology upgrades or spectrum auctions. These differences in roles also create different views among stakeholders on how this issue should be resolved.

The investigation should also provide stakeholders guidance regarding if, how and to what extent the foreseen impact could be mitigated. If we think about different relevant aspects of possible mitigation measures, the radio-technical effectiveness is obviously important but other aspects like business impact and implementation complexity should also be included to be able to assess the overall viability and “attractiveness” of each measure.

Although finding ways for co-existence has been our main driver, there is no a priori assumption that co-existence shall be possible at all costs. The investigation may lead to the conclusion that sooner or later co-existence will not be possible without serious quality deterioration of the one application, the other or both. We have not included costing in our analysis, so a financial assessment or cost benefit analysis may be required on the basis of our outcomes.

The existing Burum Interception Facility and the future 5G networks are treated equally, but the fact that Burum is an already existing operational facility is respected by starting the analysis there. Other than that, the investigation as a whole as carried out by TNO is fully agnostic towards both applications.

5.1.2 Structure of the analysis contained in this chapter

After a brief presentation of the aspects that come into play in this co-existence issue in section 5.2, we present the methodology in section 5.3 and the results of the actual analysis in subsequent sections. The chapter finalizes with a proposal how the mitigation burden *could* be shared between both applications. Based on this proposed share and recognizing the fact that possible mitigation measures which can be realized relatively quickly (within approximately three years) have priority over long term solutions[50], a dashboard overview is presented for mitigation solutions on both sides.

5.2 Influential factors

As a prelude to the presentation of the outcomes of the impact assessment, we will briefly describe the various factors of influence as they provide the necessary insights into what happens and also provide ‘hooks’ for possible mitigation. The factors are grouped into three topics (see figure). Source (5G mobile networks), Propagation and Destination (Burum Interception Facility).

The basic problem we are looking at is that emissions generated by a mobile network and their associated mobile terminals may propagate (also) in the direction of the Interception Facility Burum and enter the antenna and receiver system where due to the broadband nature of the 5G signal, it effectively raises the noise floor of that system. Consequently the performance of that system may be degraded.

5.2.1 Factors related to the source (5G networks)

In general terms, the amount of signal energy that ‘escapes’ in the direction of Burum depends on a transmitter’s radiated power and the height of the transmitter relative to its local surroundings. Due to the fact that in a mobile network both the emitted power as well as the antenna height outweighs that of mobile terminals, we are most concerned with how the base stations (BSs) are configured and deployed[51].

The maximum transmitter power plays a role but the instantaneously transmitted power is a function of time and frequency. The 5G signal is a complex construct in which signal power can be assigned flexibly in both dimensions. Fluctuations are caused mainly by variations in (user) traffic load although short term fluctuations can also be expected due to the large peak-to-average ratio of OFDM type of signals as applied in 5G. In quiet periods, mobile network emissions are reduced. Maximizing a BS’s transmission power is not a goal in itself. In order to control interference levels and to save energy consumption, this is subject to optimization. The signal energy emitted in a certain direction is determined by the antenna characteristics. In the conventional approach three or more sector antenna’s cover the entire azimuth range. The antennas have a certain downward tilt to avoid the introduction of self-interference outside the intended coverage area of the cell of the BS, which has actually a similar effect on emissions towards Burum (assuming the sector antenna is pointed in that direction). The sector antenna pattern has a main lobe wide enough to realize sufficient circular coverage from that particular site. With the use of mMIMO antennas or Adaptive Antenna Systems, the antenna pattern becomes dynamic in time (on a milliseconds timeframe). Ultimately, its shape depends on the actual position of mobile terminals to which individual beams are pointed as well as on the built up environment which plays a role in the constructive addition of reflected signal components. With the assistance of the terminals the base station will be able to do a sounding of the radio behavior of its

[50] The next chapter also addresses the long term co-existence situation.
[51] That does not mean that mobile terminals could never affect Burum. This will be discussed later.

environment and adjusts the antenna pattern accordingly to optimize the signal quality at the terminal side.

The higher the base station antenna is erected relative to the surrounding built up area, the higher the probability of signal energy escaping in horizontal direction towards Burum. In terms of impact, there is therefore a clear difference between a macro configuration with high sites and a small cells deployment where antennas are mounted at roof-gutter level causing the signal energy to stay contained between buildings. This also implies that Base Station deployments in rural, open areas can have more impact compared to deployments in cities and alike. Due to the fact base stations in those parts of the country typically have large service areas, the tilt angle is fairly small which aggravates the issue.

The density of base stations in a particular area is clearly influential. Particularly in urban areas cell sizes are reduced in order to optimize capacity. Although tilt angles are increased in the process, a net accumulation of signal energy takes place.

From this inventory the conclusion is justified that the impact of 5G networks on Burum is determined by the combined result of local network configuration specifics and (local) environment characteristics.

5.2.2 *Factors related to propagation*

The radio propagation conditions along the path between the source (5G Base Station) and the destination (Burum Interception Facility) determine strongly the amount of energy actually arriving at Burum and in what spatial shape. We neglect here the propagation conditions in the locality of a Base Station but discuss propagation effects at larger distances. The simplified figure below shows typical propagation paths which come into play.

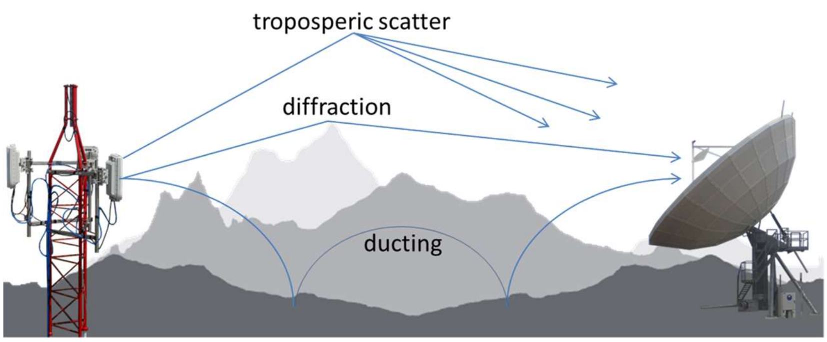

Figure 12: Simplified view on relevant propagation modes in this co-existence study.

The C-band (3.5 GHz) is situated in the lower part of the SHF range. In this part of the spectrum, radio behaves approximately like visible light so in vacuum conditions, propagation is in almost straight lines (limited bending) and with clear shadow effects in case of obstacles. In practice this means that at distances from Burum until or just beyond the radio horizon (approximately 30 km[52]), propagation loss is directly determined by distance, the presence of obstacles which (nearly)

[52] Based on 25 m (BS) and 5m (Burum) antenna heights

cross the line of sight and the occurrence of ground reflections. Further away, the earth introduces additional attenuation, so signals are more strongly weakened. Beyond a certain distance (between 50 and 100 km) the atmosphere starts to play a role also. The lower part of the troposphere regularly shows properties which can cause radio signals in this band to propagate with little loss across several hundred kilometers.

The refractive index of the standard atmosphere without anomalies has a value of -39N/km. This equates to a virtual Earth radius which is 33% larger than the real one. A non-standard atmosphere situation occurs when the atmosphere stabilizes, for example when under the influence of a High Pressure weather system. Descending air masses within a High Pressure system will produce a *temperature inversion* which changes the refractive index of the atmosphere. This may be a very significant change. For refractive indices between -39 and -157 the situation is "enhanced". Signal losses for transmissions within this region, will be greatly reduced compared to the Standard Atmosphere situation. A special situation occurs when the refractive index equals to -157N/km or less, as the bending of radio signals will then equal the Earth's curvature. This is called a *Duct*. The losses may even become less than Free Space, as the radio signals are trapped in a 2-dimension layer instead of 3-dimensional space. Although the probability of occurrence of this ducting phenomenon is low (small percentage of time) it needs to be taken into account in the sharing analysis. When ducting occurs which can be in various parts of the country, the interference and it impact can increase significantly. Due to the fact a mobile network is a collection of geographically distributed signal sources, the cumulative probability of atmospheric signal contributions can be high.

The ITU provides documents[53] with statistical information regarding the chances of anomalous propagation on SHF and its effects on the propagation losses. Statistical data provides a means to estimate the *chance* that certain events may occur, not *when*. So it supports the impact assessment but it still leaves some questions open regarding how to deal with it's unpredictability in an operational context. We have addressed this in section 6.5.

The ITU-R P.452 model is considered as the best practice in the statistical prediction of the propagation loss. The model implicitly predicts which percentage of time anomalies in the atmosphere occur that lead to low propagation loss, based on statistics. The model is used as basis to derive the propagation loss (attenuation of the 5G signal in this case) as a function of distance. It predicts the minimum radio propagation loss that can be expected for various percentages of time (between 0 and 50%). In the example shown in Figure 13 can be seen that, when calculating for 1% of the time at a distance of 60 km, the predicted propagation loss is 150 dB. This means that 99% of the time the propagation loss at for that specific path over 60km will be more than 150 dB.

[53] See: ITU-R-REC-P.453-11

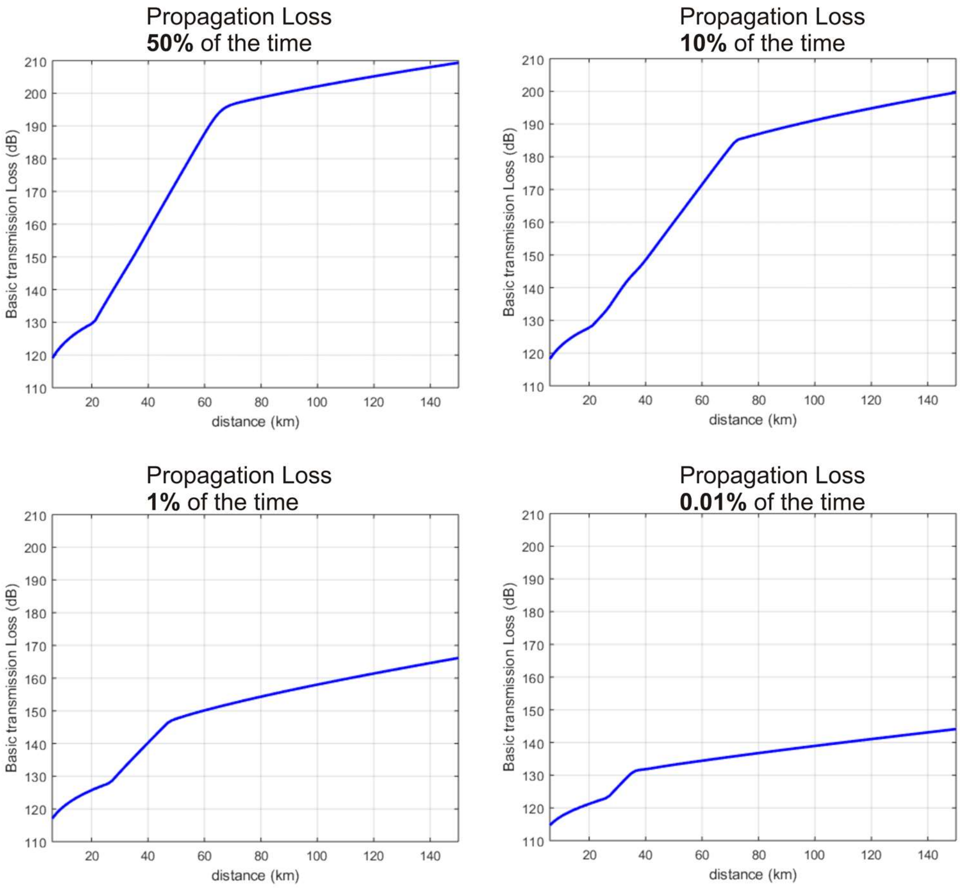

Figure 13: Propagation Loss for time percentages of 50%, 10%, 1% and 0.01% as predicted with the propagation model contained in Recommendation ITU-R P.452

The 4 plots in Figure 13 show the predicted propagation loss for a certain path at different percentages of time. What can be seen is that the mean predicted path loss, thus for 50% of the time is rapidly increasing from 130 dB at about 20 km to a value of 210 dB at 150 km. At a time percentage of 10% the curve has a similar trend, but the values are somewhat lower: 200 dB at 150km. Major differences can be seen when calculating for low percentages of time: 1% an 0.01% curves are shown. Here the predicted propagation loss is significantly lower: for 0.01% this is 143 dB at 150 km. A lower propagation loss will in our case imply a higher interference level at the Burum satellite receiver installation and results production loss when the maximum acceptable interference threshold is exceeded.

A few years ago the question was raised whether the ITU-R P.452 model assumptions were sufficiently in line with the actual situation in the Netherlands. Agentschap Telecom[54] therefore initiated a multi annual measurement campaign to assess the model against the measurements on four different trajectories (from 4 signal beacons, to Burum). The plot below is taken from the publication and shows the difference between model prediction (P.452-14) and measurements. The plot in Figure 14 indicates that the ITU model appears generally pessimistic compared to

[54] Source: L.C. Colussi et al, Multi year Trans Horizon Radio Propagation measurements at 3.5 GHz, IEEE Transactions on Antennas and Propagation, 2016.

measurements). We assessed these results against our own simulations (P.452-13) from which a mixed conclusion emerged (pessimistic/optimistic depending on the path considered)[55].

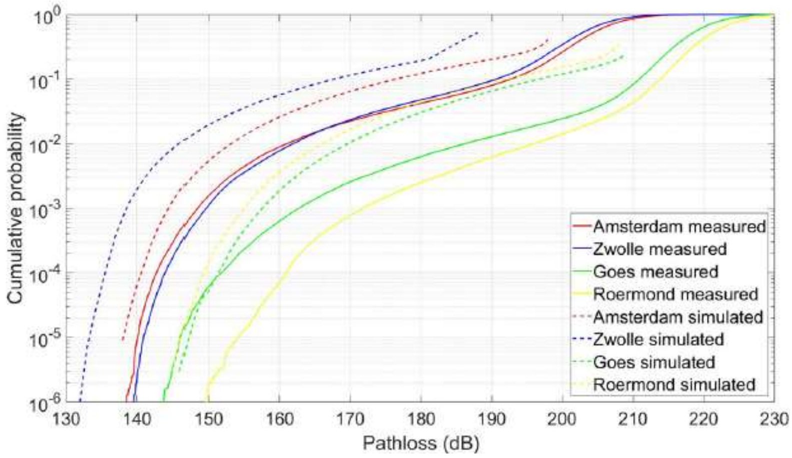

Figure 14: Diagram with plots of simulated (P.452) and measured path loss values. The plot shows The ITU P.452 is pessimistic.

5.2.3 *Factors related to the destination*

The Burum Interception Facility has been described in the previous chapter, so here we summarize the most important aspects.

The Burum Interception Facility consists of a constellation of independent conventional type satellite dishes which associated receiver chains, dishes which are operated within certain orientation boundaries, in azimuth and elevation. Depending on the chosen dish orientation, an incoming mobile network signal is amplified (or attenuated) according to the dish antenna pattern. A typical satellite dish antenna pattern has a narrow main beam and various side lobes, so the sensitivity of the dish towards terrestrial interference (as well as towards atmospheric interference components) depends entirely on the dish orientation. The dish's elevation angle is particularly important. In both the eastern and western directions the elevation angle at which satellites can be tracked is very low, which makes the Burum Interception Facility extremely susceptible to terrestrial interference arriving from these directions.

As mobile network interference enters the interception receiver system as additional (non white) noise, the noise floor within the receiver bandwidth increases which reduces the achievable signal to noise ratio and could complicate or fully prohibit successful demodulation of the wanted signal. If the current level of noise and interference measured at the receiver and a representative set of incoming satellite signals are taken as a reference, any future increase of interference due to the presence of mobile networks, induces a certain loss of interception data compared

[55] The relevance of this remark is that we have continued the use of our own P452-13 model in this investigation. This model is very close to P452-14 which was used by AT.

to the reference situation. This Production Loss is taken as the main KPI in this investigation.

5.3 Methodology Impact & mitigation calculations

5.3.1 Overview

The assessment of the impact of 5G networks on Burum and vice versa is done in the way depicted below. Calculus wise, the forward chain of calculations is most straightforward, so instead of a reverse chain the forward chain can be used in an iterative fashion. This section provides a description of the methodology followed. Additional information on specific aspects is contained in Annex C.

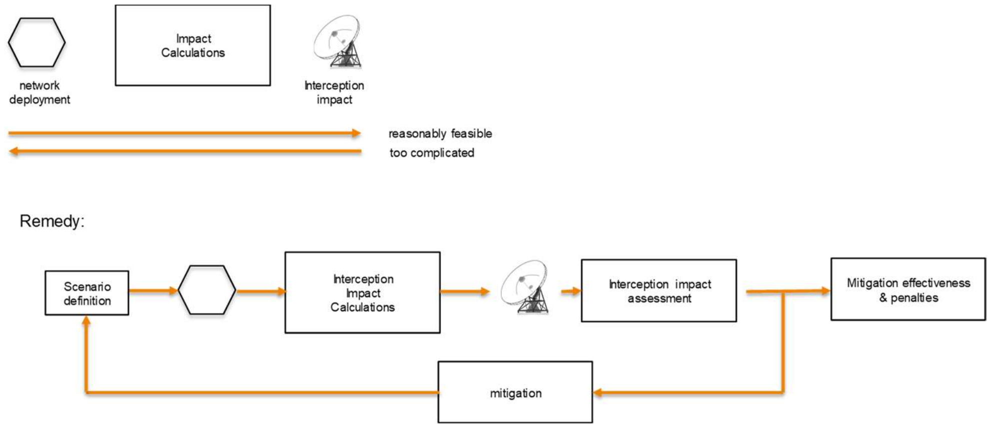

Figure 15: Followed approach in impact calculations (including mitigation).

5.3.2 Working with Fictive Transmitters with an EEIRP value

The calculation of the aggregated interference level at the Burum receiver as caused by a 5G network is done by placing a single *Fictive Transmitter* at the geographical center of each Postcode-4 (PC-4) area within the service coverage area defined by the 5G scenario. For a certain PC-4 area the Fictive Transmitter has a certain *Equivalent Effectively Isotropic Radiated Power* (EEIRP), which equals the aggregated radiated power which escapes from this PC-4 area in a horizontal direction because this direction is relevant in the co-existence calculation. A clarification to be made at this point is that the calculated EEIRP values were agnostic to the bearing angle. Although each PC-4 area has a particular known bearing towards Burum, we pretended not to know the bearing. This may seem to be very inaccurate at first sight and will therefore be explained later in this section. The EEIRP value for each individual PC-4 area was determined as follows.

We have sorted and classified all PC-4 areas in the Netherlands on the basis of two criteria, being the distribution of building height and the distribution of the percentage built up area per tile of 50 x 50 meters[56]. A classification was made into

[56] We have used clutter database provided by KPN and the public AHN2 database (Actueel Hoogtebestand Nederland).

four groups (classical downtown, business district/high rise, suburban and rural). The classifier we developed had to be aided with CBS data to optimize the classification result.

We defined for the Urban, Suburban and Rural geotypes typical local network *deployment models*. Each specific deployment model is defined by the number of base stations per square km, antenna height and tilt, and antenna diagram. The base station densities for these environments are adopted from ITU documents with IMT2020 reference configurations[57].

From each of these four sets, a few sample PC-4 areas have been chosen which have been subjected to a detailed ray tracing propagation analysis, using the network deployment models. The goal of the analysis was to calculate for each geotype and associated deployment model the value of the normalized EEIRP value (dB/km2). Annex C contains more details of the method and achieved results. As we had multiple samples per geotype[58], we were able to average the result to increase its statistical reliability. These outputs (average and standard deviation) have been stored in a library. To validate the library, per geotype, one or two PC-4 area test samples were picked blindly from the grand list for which the analysis was repeated. Results were compared with the library data. In most cases we concluded that the deviation was within 1-sigma of the average value stored in the library. Although this check was very limited in scale, the results for all geotypes together indicated the method could be adopted.

The fact that the EEIRP values calculated are agnostic to the bearing is motivated by the fact that we did not carry out a radio planning for each individual PC-4 area. This is the way an operator works, where he also optimizes the deployment to the local circumstances. Our exercise was a much more generic one where our main goal was to achieve a *reliable average value* of the normalized EEIRP which could then be applied to any arbitrary PC-4 area of the same type. Based on the law of large numbers we knew that the bearing agnostic approach would result in an error at each individual PC-4 area, but these errors would average out reasonably well for the entire collection.

The next step was the calculation of the EEIRP value for each geotype classified PC-4 area of the grand list, represented by a fictive transmitter centered in the area. This concluded the EEIRP calculations.

The 5G scenarios from our framework for which we used the Antenna Register as a basis, do not resemble these stylized local deployment models with fixed inter site distances. This raises the question how the created Fictive Transmitter list relates to these scenarios.

The underlying assumption is that the EEIRP value scales reasonably well with the chosen density in a PC-4 area. In other words, if we simply triple the base station density, the EEIRP value would increase with approximately 5 dB. Our propagation simulations demonstrated that is quite accurate. This allowed us to apply scaling factors to the EEIRP values. Hence, our 5G scenarios work with site density values

[57] Source: ITU-R, *Guideline for evaluation of radio interface technologies for IMT-2020*, M.2412-0, 11/2017

[58] Focus has been on modelling urbanized areas. Rural case is more straightforward.

per PC-4 area, which allows us to appropriately scale the Fictive Transmitter for any particular 5G scenario.

The model developed allowed to obtain estimates of impact (ERIP) or impact reduction of:
- antenna height adjustments,
- transmitted power adjustments,
- changes in carrier load conditions,
- use of massive MIMO antenna systems.

In order to be able to estimate the impact of the use of Adaptive Antenna Systems, a separate Monte Carlo simulation study has been conducted, applied to each of the aforementioned 5G deployment models, to get estimations of the expected radio decoupling in case of the use of massive MIMO antenna technology, compared to conventional antennas.

5.3.3 *Calculation of long distance propagation loss*

The next step in the procedure was to calculate for each trajectory (PC-4 area to Burum) propagation loss statistics using the ITU-R P.452-13 model as well as the antenna gain at the Burum side which provides the individual interference contributions. These interference contributions are added in two different ways, i.e. assuming *full correlation* in propagation (gives lower bound estimate in Production Loss) and *fully uncorrelated* propagation (gives upper bound estimate in Production Loss). This difference will be explained.

Extremely low propagation loss values on a certain long distance trajectory due to atmospheric conditions are short in duration and have a small probability of occurrence. If these contributions come from a large group of Fictive Transmitters, they may be added at the receiver under the uncorrelated assumption because the probability that they overlap is practically zero. Propagation loss values with a higher probability will occur during longer periods of time. The uncorrelated assumption gets violated for these long term losses. Still simply adding these values then leads to overestimates of the aggregated interference (exceeding 100% which is not possible). The fully correlated assumption assumes full stochastic coupling of interference signals coming from larger numbers of fictive transmitters. For propagation loss values with a higher probability and longer time duration, the fully correlated assumption then becomes relatively more reliable compared to the other. Still, the real expected value will be in between these boundary values.

5.3.4 *Calculation of the Production Loss*

Finally the Production Loss figure was calculated. This figure is based on a combination of the statistical distribution of the incoming aggregated interference and the distribution of loss of interception data as a function of the carrier to (noise+) interference ratio. Annex C provides more details (except for classified information[59]).

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[59] A separate classified report has been issued by TNO which contains the results of measurements in Burum and diagrams which relate the Production Loss to the rise of the interference level in the receiver. Reference: TNO 2018 R11146, October 2018

5.3.5 *Impact 5G on Burum versus Burum on 5G*

Contradictory to our explanations up to this point, the *presentation* of the results will be given in the opposite order, in recognition of the Burum Interception Facility being the incumbent application and possible “victim” of the future introduction of 5G networks which cause in-band radio interference. The BIF has a key performance criterion which is the maximum allowed production loss (PL), expressed as a percentage of a total production of intercepted data under a set of assumptions. This criterion is used in this investigation. In the presence of 5G network deployments which would operate in the same band, a certain radio decoupling is required to ensure that the Burum Production Loss criterion is met. We present the required decoupling values for each of the deployment scenarios and discuss if and how 5G networks could reach this level of decoupling. So, in this part of the analysis, the decoupling challenge lies on the mobile network side. We present ways how decoupling could be achieved. These mitigation measures have a certain effectiveness but also impact the performance of the mobile network on which these measures are applied. The mitigation measures we have identified and their merits are described. This summarizes the content of section 5.4.

The second step is to consider what the impact would be on the performance Burum if 5G mobile networks would be deployed in this band without any particular restrictions. We will consider the production loss effects and discuss ways how Burum could protect itself against aggregated emissions from these networks. In this part of the analysis, the mitigation challenge is entirely on the Burum side. In a similar way, these measures have their effectiveness but also their penalties to the performance of Burum. Hence, these measures are also described with their merits. This is covered in section 5.5.

5.3.6 *Interpretation of results*

The quantitative results presented in this chapter have been obtained via modelling, simulation and straightforward calculations as described in this chapter and further documented in Annex C, and summarized here. The complexity and the combined statistics involved prohibit a detailed end-to-end modelling of the co-existence situation. The modelling has been targeted at capturing the main system and/or physical characteristics, and on validation of individual parts of the model ‘chain’ where possible. Also the statistics involved have been broken into logical pieces to keep the analysis tractable. As this approach prevents an end-to-end assessment of the reliability of the outcomes, care should be taken with the interpretation of the absolute figures presented. They merely provide a coarse but useful prediction of effects that can be expected both in terms of impact as well as effectiveness of mitigation measures. In order to prevent exact figures to be perceived as ‘ground truth’, we have abstracted these findings using color schemes, to allow readers to receive the main messages.

5.4 Impact of Burum on 5G roll out in the Netherlands

5.4.1 *Reference KPI for Burum*

In 2008, the maximum allowed Production Loss as formulated by the Ministry of Defense was **0.0038%**. This Production Loss criterion has not been recalled or adjusted since then. So, it still applies and is also taken as the reference performance value in this investigation. This has been labelled as “Gold”.

The Production Loss is determined from the combined statistical distribution of the interference levels and the statistical distribution of intercepted satellite signals.

5.4.2 Required decoupling in presence of 5G

The diagram below shows the amount of decoupling that is required for any of the 5G scenarios defined, assuming the “Gold” label. A minimum exclusion zone of 20 km around Burum is assumed in all cases, because also other effects like receiver blocking come into play at shorter distances.

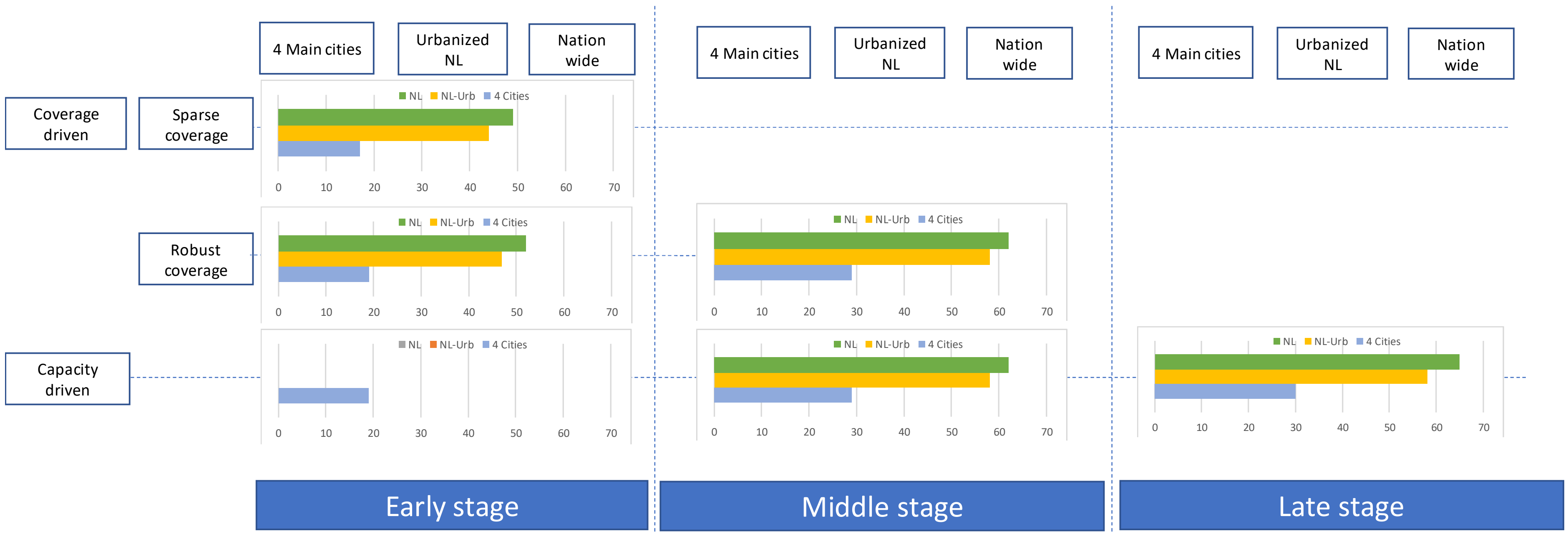


Figure 16: Minimum decoupling values (dB) for the 5G scenarios considered, to reach a maximum PL of 0.0038%. A minimum exclusion zone of 20 km is applied.

The diagram clearly illustrates that the required level of radio decoupling is directly related to the geographical scope, density and utilization of the interfering 5G network. This means that the decoupling required depends both on the operator's roll out strategy as well as the amount of traffic his network handles, which is directly related to the level of adoption of 5G services on his network.

As 5G based services are expected to just blend into the operator's services proposition, any mobile network will sooner or later become fully 5G capable just like we have seen in the past with 4G/LTE technology. Likewise, it can be expected that nationwide presence with 5G is an obvious ultimate goal of a mobile operator.

It is to be noted that the "heaviest 5G scenario" in our framework (Scenario S3e) may become reality earlier then we have predicted here. Based on past experience and because of the fact that 4G/LTE will still be around for quite some time, it seems unlikely that it will occur within 5 years after the introduction of 5G, but there is no absolute guarantee. It also means that the highest minimum decoupling value mentioned in the diagram shall not be considered as the *maximum value* in this 5G-Burum co-existence scenario.

Furthermore, it is to be noted that *the decoupling values presented here are generally considered in spectrum management as large*. These indicative values reveal the severity and complexity of this spectral co-existence dossier.

5.4.3 *Default mitigation[60]: exclusion zone*

The application of a geographical exclusion zone is a well-known and passive mitigation measure which we will address first. The way we frame the case is to first show how far away a 5G network should be kept from the Facility, after which technical mitigation measures are discussed which are aimed at getting the network closer to Burum. A minimum exclusion zone of 20 km is maintained.

The diagram below shows the remaining decoupling to be accomplished as a function of the exclusion zone which we treat here as a variable. If the diagram is read from right to left it shows how much radio decoupling must be achieved if the deployment (and subsequent utilization) approaches Burum. We have shown it for Scenarios S3a (nationwide, robust coverage; early adoption; early stage) and S3e (nationwide, capacity, evolved; late stage). See also Figures 11 and 16.

[60] The term default mitigation should not be interpreted here as 'mitigation of first choice'. It is to distinct this passive measure from all other active measures. If one does nothing, the default situation has to be an exclusion zone. For Burum we use the term default for Production Loss with exactly the same interpretation.

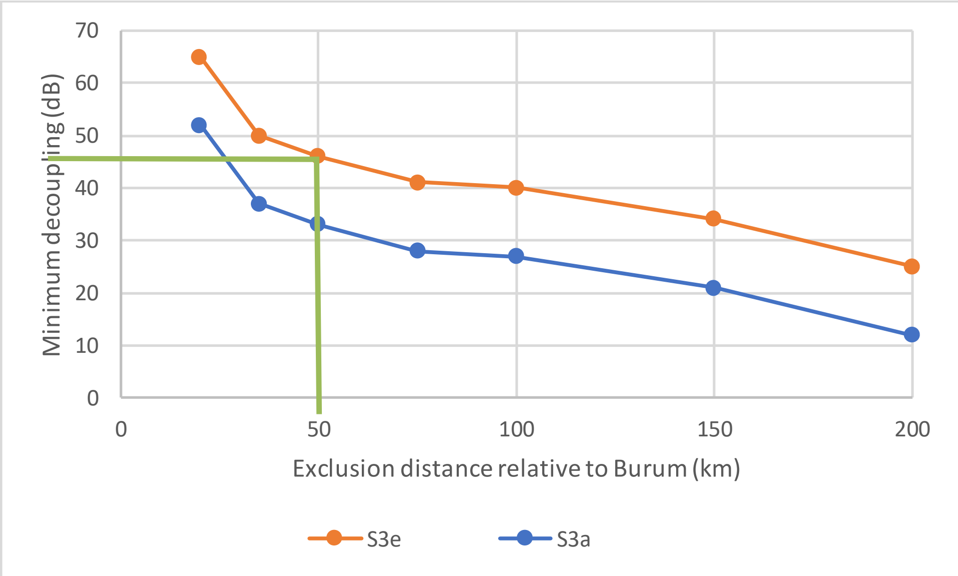


Figure 17: Minimum decoupling requirement as a function of exclusion zone. The green lines indicate the point where the decoupling curve starts to bend exponentially.

Both curves consist of two concatenated segments:

- a segment on the right between 100 and 200 km with a *concave* curvature, which is relatively flat;
- a segment on the left between 20 km and 100 km with a *convex* curvature showing an increasing negative slope at shorter distances.

The convex segment in our diagram has its center point at 50 km in case of Scenario 3e. Closer than 50 km, the radio decoupling requirement increases quickly as the distance to Burum reduces.

What we see here is a mix of normal radio propagation behavior and how the network is deployed over the country. This means that there is a region where mitigation is rewarding in terms of territory that can be regained. The situation within the 50 km range *is a clear indication that the most northern part of the country (notes as NN-NL) poses a specific problem*. As we will see later, the nearby cities Groningen, Leeuwarden and to a lesser extent Assen contribute to this problem. The map below shows the topological interpretation of the 20 km and 50 km borders.

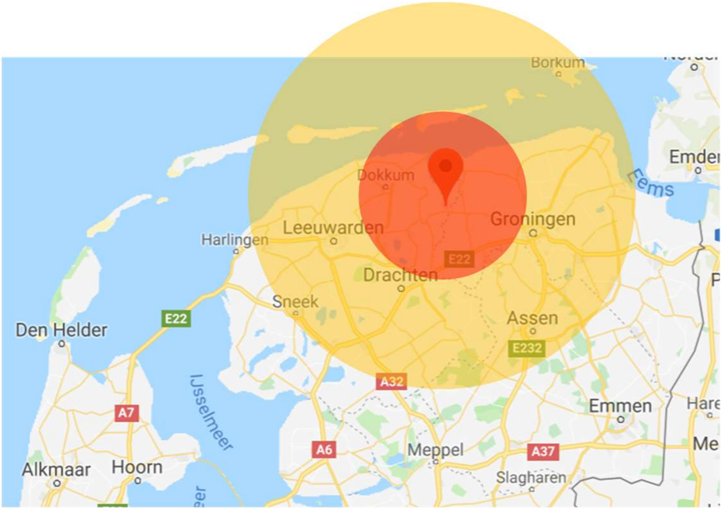


Figure 18: The concentric areas around Burum defined by 20 km and 50 km contours.

Hence, we will discuss the NN-NL problem separately in this chapter. In the remainder of this section, we keep a mitigation requirement of up to 45 dB in mind as an order of magnitude needed for 5G networks for the period up and including the late stage in our framework (approximate time stamp: 2028). This 45 dB value can be read from Figure 17. This value is associated with the most mature/evolved scenario of our framework. **It is to be interpreted as an <u>indication</u> of the decoupling that would be required between the Burum Interception Facility and an actual 5G network, if this real-life network would be deployed and utilized along this definition.** To be clear, this means that in an evolutionary development of 5G technology penetration and adoption, this would not be the instantaneous requirement but the requirement that will be reached at some point in time.

5.4.4 *Mitigation options in 5G networks*

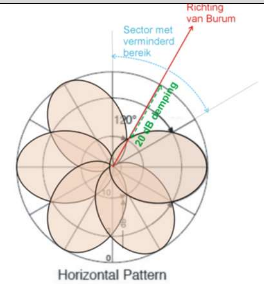
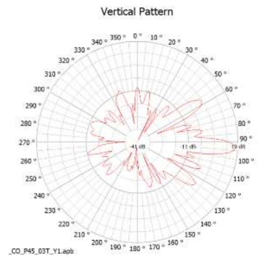
The following few pages provide an overview of mitigation options which could be considered for application in a mobile network. The assessment aspects for each of the considered measures is listed below.

Table 6: Aspects included in the assessment of 5G related mitigation measures

Concept description	Explanation of the mitigation principle
Mitigation effectiveness	Level of radio decoupling that can be expected, generally or under specific conditions. If not quantifiable than at least qualitatively.
Reliability	The reliability that the radio decoupling is sustainable or at least predictable.
Technological maturity	The maturity of the enabling technology. Is it still in an R&D stage or do we also see applications with this technology.
Implementation complexity	The complexity involved in engineering to arrive at an operational solution.
Business impact	The impact in terms of reduced capabilities or performance of the network or efforts/costs involved to maintain capabilities or performance at the same level. Only qualitatively.
Preservation of level playing field	The extent to which the measure has effect on the level playing field principle that the regulator needs to ensure in the commercial telecommunication market.

Measure	**Exclusion zone**
Concept description	Strict geographical separation between the Burum Interception Facility and any Base Station of a mobile network operating in the same band, such that a predefined impact criterion is met. This means Base stations cannot be located within this zone. The impact criterion must be determined on the basis of a predefined network configuration specification, taking into account interference aggregation effects.
Mitigation effectiveness	When a safety margin is incorporated in the criterion to account for propagation variations, the effectiveness against long term interference is relatively high, in case of distances where ducting effects cannot be expected (<<100 km). Base stations further away may cause short term interference. An exclusion zone dimensioned to also protect against this type of interference will be very substantially larger (few hundreds of km from the Burum facility). See also reliability. When 5G networks evolve and site densities increase, the criterion may not suffice anymore unless this densification has been taken into account at the very beginning in the development of the network configuration. It is recommendable to determine the largest possible exclusion zone, under clear assumptions to be defined (interference level measured according to a certified procedure), in advance in order to provide deployment assurances to operators.
Reliability	Level of reliability is directly related to the margin included in the determination of the exclusion zone. Uncertainties about propagation effects which specifically play a role at longer distances, increase with larger exclusion zones, requiring even higher margins.
Technological maturity	There is no or limited technology involved in the implementation of an exclusion zone. Can be readily applied.
Implementation complexity	The implementation complexity is low.
Business impact	The business impact to operators can be substantial in case the exclusion zone occupies substantial parts of the country (e.g. size of a province or more). The impact is the gap in the 5G service area that is created, which can be quite problematic for a national operator.
Preservation level playing field	The exclusion zone applies to all operators in the same way (assuming no frequency dependent exclusion zone). Hence, the level playing field is preserved.

Measure	**Reduction in transmission power**
Concept description	The transmission power applied by the Base Station can be reduced which subsequently reduces the emitted power by the antenna and henceforth the interference level within the bandwidth where the transmissions take place. The maximum transmit power is often related to system/hardware (ranges from a few Watts for small cell equipment compared up to 200W for a 5G macro BS). The network applies transmit power control strategies (e.g. green ICT), to adapt the transmission power to actual needs. This is also an important aspect in the discussion on RF exposure reduction of mobile networks. Besides the absolute transmission power as such, it is of relevance how this power is spread across the transmission bandwidth as the power spectral density at different frequencies within the transmission band is what matters to Burum.
Mitigation effectiveness	The mitigation effectiveness is relatively high but depends on the actual reduction that is applied, and how this translates into a reduction of the power spectral density. In case of a flat distribution over the channel, a 5 dB reduction in the transmission power results in 5 dB reduction in the power level measured within the transmission bandwidth. As the measure applies to individual base stations, the aggregated mitigation effectiveness scales with density growth of the network. Considered in isolation, the power reduction cannot be made infinitely high as this jeopardizes a normal base station operation (a small cell would then be a better alternative)
Reliability	The reliability is high since there is a straightforward relation between transmit power and interference level.
Technological maturity	Networks allow the use of downlink power control for interference management and energy saving goals. Providing external dynamic power control instructions to the network is possible through the LSA concept (see elsewhere in this report) of which implementations already exist (e.g. for the 2.300-2.400 MHz band)
Implementation complexity	This is of moderate complexity. A power control protocol would have to be implemented, preferably as part of an LSA concept tailored to this co-existence issue.
Business impact	The business impact of an imposed transmit power reduction is a reduction of the cell size which would happen everywhere where the power limitation applies. Depending on the magnitude of the power reduction, this can cause capacity or even coverage gaps in the network where/when the measure is applied. If the reduction has a permanent status, this means the operator may have to densify to repair these effects, which would reduce the mitigation effect and increases network costs. A flexible transmission power reduction would lead to temporary network effects which could be handled by the operator if it is known in advance. The disadvantage of transmit power reduction is that it affects a BS performance in all directions rather than only in the direction of Burum. Hence, it is a very coarse policy.
Preservation level playing field	If an operator is forced to reduce his EIRP footprint through transmission power reduction, the application of small cells can help to achieve this. A fixed mobile operator may be in a better position to implement this compared to a Mobile only operator.

Measure	**Antenna related measures (conventional)**
Concept description	Antenna related measures are alternatives to transmit power adjustments in the goal to reduce the radiated signal energy. They deal with directivity of emission, which is an important difference to the previous measure. This item focuses on what can be done with conventional antennas: 1. Increasing antenna tilt 2. Sector antenna removal  
Mitigation effectiveness relative to target (per snapshot)	Ad 1: well known interference reduction measure within one network. Quite effective as significant directional gain reduction can be achieved already at relatively small tilt angles due to the narrow beam in vertical direction. Ad 2. A brute force method is the removal in a mobile network of a sector antenna which is optimally aligned with the bearing towards Burum. Although the two remaining sector antennas will cause sidelobe emissions, the reduction can be in the order of 10 dB or more. If a six sector arrangement is chosen, the measure is more accurate with less impact as each sector antenna has a much smaller width. For all options: as the measures apply to individual Base Stations, the aggregated mitigation effectiveness scales with density growth of the network.
Reliability	Both measures are quite reliable. In urban environments the effectiveness will be reduced due to the occurrence of signal multipath, which tends to fill the created gaps.
Technological maturity	The solutions mentioned are well known and practiced in radio engineering.
Implementation complexity	Ad 1: Implementation complexity of tilt adjustments is very small. Ad 2: The complexity here lies in the required re-engineering of the macro network because the coverage footprint of a base station changes substantially. Moreover, the sectoral orientation of the base stations becomes a function of its location. Resolution of capacity and coverage gaps may require densification.
Business impact	There is a business impact because the macro network requires adjustments, which can be substantial and costly. The increase in antenna tilt may have synergy with capacity improvement measures. The option with the highest impact is option 2.
Preservation level playing field	These measures would work out in more or less the same way for different operators. No distortion of the level playing field.

Measure	**Antenna related measures (adaptive antennas)**
Concept description	Antenna related measures are an alternative to transmit power adjustments in the goal to reduce the radiated signal energy. They deal with directivity of emission, which is an important difference to the previous measure. This item focuses on what can be done with adaptive antennas (phased array, mMIMO): 1. Increasing antenna tilt 2. Creating a null in the antenna diagram 3. Sector non illumination **Remark**: Massive MIMO is considered in the telecommunications market as an important option to be applied in the 5G network roll out where possible. We therefore calculated for a subset of scenarios from our framework the estimated residual impact on Burum if this technology would be applied everywhere in the network. See annex D and also next attribute in this assessment.
Mitigation effectiveness	Adaptive antennas (massive MIMO) have an inherent mitigation effect because the average directional gain in any particular direction is much less compared to a conventional antenna. Monte Carlo simulations conducted by TNO with urban and suburban deployment models (see Annex C) indicate additional decoupling values between 3 and 11 dB compared to a conventional sector antenna in the same situation, depending on the deployment model . Ad 1: Antenna tilt. This will be at least as good as with a conventional antenna Ad 2: The inherent flexibility in the antenna diagram makes it straightforward to create nulls in the diagram Ad 3: See second option. a sector of arbitrary shape could be discarded.
Reliability	All measures are quite reliable. In urban environments the radio decoupling effectiveness will be reduced due to the occurrence of signal multipath, which tends to fill the created gaps.
Technological maturity	Adaptive Antenna Systems on the level of massive MIMO are relatively new, but solutions are available in the market. Technology will be continuously improved in the coming years.
Implementation complexity	Adaptive Antenna Systems and particularly the class of massive MIMO are inherently complex but the additional complexity of programming these antenna pattern restrictions is limited and may be facilitated by the vendor.
Business impact	There is a business impact because these restrictive measures reduce the achievable spectrum efficiency, but operators are already strongly incentivized to turn to Adaptive Antenna Systems in their networks, which limits the additional burden to implement the mitigation measure. The massive MIMO concept in mobile networks has the fundamental capability, particularly in built up environments, to ensure a certain link quality at each terminal, even when the direct LOS path is blocked. This implies that a directional gain restriction in a particular direction can be more easily repaired in the service coverage area. In open environments this multipath gain is much more limited.
Preservation level playing field	These measures would work out in more or less the same way for different operators. No distortion of the level playing field.

Measure	**Antenna height reduction**
Concept description	The Base station antennas are mounted on a pole or mast at a certain height relative to ground level. The height together with the tilt angle of the antennas determine the shape of the service coverage area of the base station. Reduction of the height of these antennas is a measure to increase the radio decoupling between the base station and Burum.
Mitigation effectiveness	The antenna height reduction is in general terms an effective measure because it reduces the radio horizon, and henceforth the strength of the interference of the component directed towards Burum.. For example, a reduction from 25 meters to 6 meters height, reduces the radio horizon distance with a factor 2. The measure is particularly effective in urban areas because the transmitted signals remain captured between the buildings. For example, simulations have indicated a reduction in signal energy escaping from a city area of 15 dB (dense urban) and 9 dB (urban) when going from 25 meters to 6 meters in a typical city environment (all other factors equal). The adjusted height level should be well below the average local building heights. The net effect of this measure is less because more sites need to be built to reach the same coverage level, but still positive. Operators can also evaluate for new sites whether 'hiding' the new site behind an individual high rise building (in between the site and Burum) would be possible without losing intended coverage. There is a natural tendency to apply lower antenna heights in case of small cells (see also small cells assessment).
Reliability	This is a measure with high reliability but a dependency remains on external environmental factors as they can influence mitigation effectiveness.
Technological maturity	This is a technologically mature measure.
Implementation complexity	The implementation complexity can be high. Existing sites may be quite limited in accommodating substantial antenna height adjustments, so quickly new sites with associated infrastructure support would be needed at the wanted height. Additional sites would also be needed to compensate for cell size reductions in case a move would be made to low antenna heights.
Business impact	The business impact of (imposed) antenna height adjustments is high to very high. The impact concerns adjustment or renewal of existing sites and the necessary expansion of sites to maintain the same coverage level. If the operator already has planned capacity expansion via small cells, then the low heights approach aligns with his business goal and the business trade-off will then be different.
Preservation level playing field	This measure potentially distorts the level playing field because site acquisition challenges can be different for different players.
Other	Lowering the antenna heights may be or get in conflict with regulations on RF exposure. Operators need to comply to ICNIRP but a growing group of municipalities apply a stricter regulation.

Measure	**Small cells**
Concept description	Small cells are an option for operators to increase the network capacity locally, i.e. in hot spots or hot zones like shopping streets. 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.
Mitigation effectiveness	The combination of low antenna height and low transmitter power make small cells a viable candidate for interference suppression. To get a coarse estimate of the effect, we replaced in a PC-4 downtown area in Groningen the macro network with a small cells grid (ISD of 200 m instead of 500 m in case of the macro network). This led to a reduction of approximately 20 dB of signal energy that escaped from this area. The replacement in this way is not accurate but provides the order of magnitude of the mitigation effect.
Reliability	This is a measure with high reliability but a dependency remains on external environmental factors as they can influence mitigation effectiveness.
Technological maturity	Small cells technology is a known technology but also still under development with the goal to make them fully nonintrusive in their environment and to ease installation requirements.
Implementation complexity	The implementation complexity of small cells is quite high as each small cell requires site permission and the availability of power and backhauling. The use of small cells to create a coverage layer in an urban area is a major challenge as large numbers of sites with suitable locations would have to be found. Application of small cells outside urbanized areas is not considered an option at all.
Business impact	The business impact of small cells depends on their application. If they are applied in the way they are meant (add capacity), then a normal business tradeoff (costs-benefits) can be made. If they are to be used instead of the macro network to create service coverage in urban environments, the business impact is very high.
Preservation level playing field	This measure potentially distorts the level playing field because site acquisition challenges can be different for different players.

Measure	**Traffic related measures**
Concept description	The load of a NR Downlink Carrier is largely determined by the offered traffic. Reduction of traffic on the mobile network is a mitigation measure because the emitted power of an NR carrier in the downlink is nearly proportional to its traffic load (signaling data is not/hardly sensitive to carrier load).
Mitigation effectiveness	The effectiveness can be very substantial due to the direct relationship between load and interference level, and the fact it applies to each individual base station. For example, the network load during the night is much smaller than during the day, with a subsequent reduction in impact on Burum. For example, simulations have indicated that an overall equal carrier load reduction, in a scenario with 5G deployed in the four main cities, from 60% to 30% induces an additional decoupling loss of approximately 3-4 dB in Burum. In the early phase of 5G adoption, we expect the traffic load on 5G carriers in this band to be relatively modest but growing. Hence, there is inherent decoupling. Over time, the traffic will grow and maybe quite fast. Hence this initial, natural decoupling gain will be temporary. Intentional traffic load reduction on the macro network requires offloading techniques. Offloading is technically possible to small cells (outdoor and indoor) which have a much smaller interference impact, to unlicensed spectrum (5GHz) or to higher frequencies such as the 26 GHz band.
Reliability	The initial natural decoupling gain is as reliable as its prediction. If 5G will grow much faster unexpectedly, this affects reliability. In case of intentional traffic offloading, the reliability depends on the offloading mechanism that is applied. If the offloading is fully deterministic, then the reliability is high. If statistical criteria are applied to steer the offloading process, than the reliability of the measure is reduced.
Technological maturity	The technological maturity of traffic offloading mechanisms is relatively high but may bring some new aspects in 5G, which is still under development.
Implementation complexity	Traffic offloading techniques in 5G will be part of (automated) network management tools that come with the network solutions provided by industry.
Business impact	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 3400-3800 MHz is considered by operators an important band to offload *to*. Hence traffic reduction in this band reduces its value in this respect. Offloading would have to be done to higher bands (licensed or unlicensed) which requires network densification.
Preservation level playing field	Traffic reduction techniques will be easier to apply for mobile operators who also have a fixed access network available to offload to (Fixed-Mobile convergence). Hence, this measure does affect the level playing field.

We finalize this assessment with a few remaining suggestions and points of attention:

- A technique which is applied in 4G and 5G networks to provide more robust reception conditions to mobile terminals is to offer the same data via different base stations. This technique increases the carrier load of individual base stations. Omitting this feature helps to reduce the interference impact.
- Given a certain offered traffic load, the Burum interception system is susceptible to how the carrier capacity is exactly utilized both in frequency and in time:
  - In the frequency domain, a fully randomized occupation of available resource blocks is the best strategy in case no a priori indication can be given about the relevance to Burum of particular frequency channels. In this way the 5G carrier's signal power is best spread across the channel it occupies, resulting in a more or less uniform power spectral density across the channel and henceforth creating a flat increase of the (noise + interference) level at the interception receiver in Burum.
    Later on in this chapter, we discuss the case where knowledge about relevant channels is used in the co-existence arrangement.
  - In the time domain, 5G TDD networks have strict synchronization requirements in order to avoid intra and inter network interference. This leads to a reduction in degrees of freedom in the dimensioning of mobile networks, but also to predictable patterns of the aggregated interference signal in the time domain, which helps Burum to anticipate on temporarily stronger interference levels.
  - A certain downlink to uplink ratio (DL/UL) is applicable on the capacity reserved on a carrier. The strict synchronization requirements will probably also dictate the harmonization of the frame structure to be chosen and henceforth to align the DL/UL ratio. Given a certain downlink traffic flow, the preference would be to spread this traffic across all available resource blocks in order to minimize and equalize the average power spectral density across the entire channel (see also first sub bullet).

5.4.5 Discussion and subconclusion

This overview illustrates that from a technical point of view there are several ways with a 5G network to increase the radio decoupling with Burum so to reduce the exclusion zone. The estimated decoupling values which we have obtained via inspection and/or simulations have a range of a few dB up to more than 20 dB. There is little doubt about the technical viability of the measures proposed as most of them already exist and practiced in 4G (e.g. small cells) or they will be part of the 5G solution portfolio provided by industry.

What they have in common in most cases is that it requires densification in some form to repair the effect of radiated power suppression. This reduces the net achievable radio decoupling with Burum in practice and can lead to serious business penalties, depending on the measure considered.

This means that the ratio between mitigation effectiveness and business impact is important. A very good example is the exclusion zone: it is effective but only within a limited area around Burum. Further away, it's relative effectiveness reduces substantially while the penalty in terms of territory which cannot be deployed with 5G in this band increases at least proportionally to the size of the area.

The application of multiple measures in order to reach the mitigation target of 45 dB is not as effective and recommendable as it may seem. The measures proposed are not fully independent and the application of multiple measures can have a disproportional impact on the network complexity. Although we did not perform cost benefit analyses, it is certain that stacking some of these measures will disproportionally increase RAN network related cost in comparison to the practically achievable suppression. Hence, the 45 dB mitigation target for future 5G networks is considered not very realistic.

The need for mitigation will increase as time progresses, as 5G networks will evolve and grow with growing traffic demand. To the extent this expanding mitigation requirement applies to the mobile network, a few footnotes need to be added:

- The costs associated with the continued development of mobile networks will increase substantially more compared to when this mitigation requirement would not be applicable (cost increase more than proportional with every dB additional decoupling loss). This affects the long term prospects of mobile networks in the Netherlands;
- The effectiveness of all mitigation measures applied in the Netherlands will deteriorate relatively because the influence of 5G networks in this band particularly from Germany will become stronger. The impact of networks deployed in Germany upon Burum was assessed by TNO in 2008 and is recaptured here in section 5.5.2;
- In the licenses for 5G frequencies certainties will have to be provided to the licensee regarding rights and obligations. This means it must be clear beforehand which co-existence criterion will be applicable, and when.

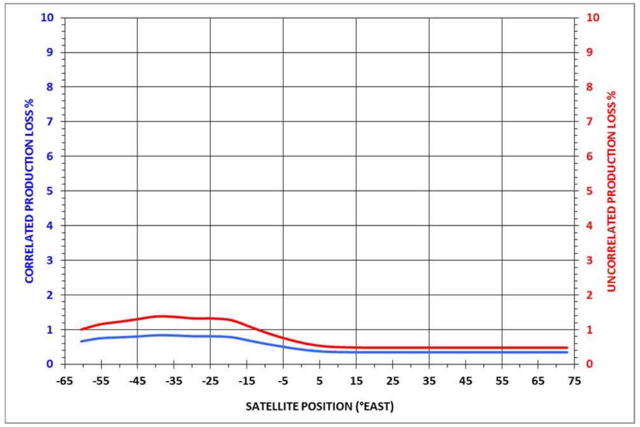
We will come back to the mitigation matter for 5G networks later in this chapter.

5.5 Impact of 5G on Burum

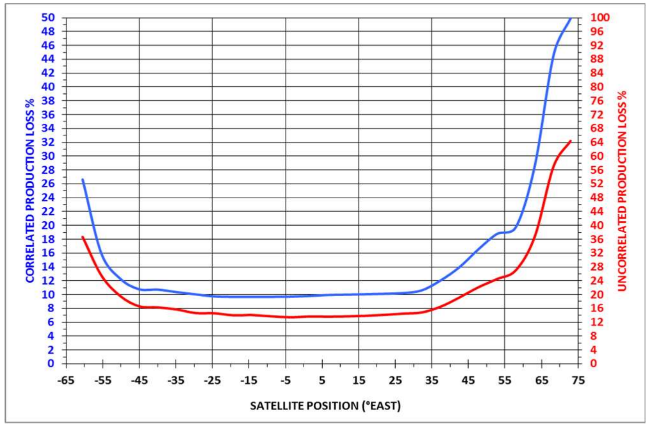
5.5.1 Production loss estimates

We will present here the production loss figures which would result from future 5G networks present in the Netherlands. The framework of 5G scenarios is used to show how the Production Loss behaves for different 5G deployment situations. These results are coherent with our results from section 5.4 but this provides another way to look at the co-existence problem which gives some additional useful insights.

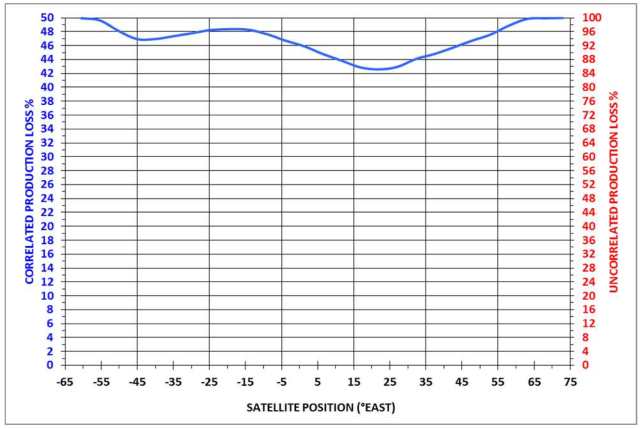
The production loss figures are presented for the ‘fully correlated’ and ‘fully uncorrelated’ assumption. This refers to the level of propagation dependent correlation between interference signal contributions arriving at Burum. The real experienced average loss value will be somewhere in between these boundary values for low production loss values <10%. The higher the production loss value reaches out well above 10% for the uncorrelated assumption, the less reliable this value becomes, so the real world value would stay closer to the blue curve. Please note that the scales on the left and right hand side are not the same in all cases.



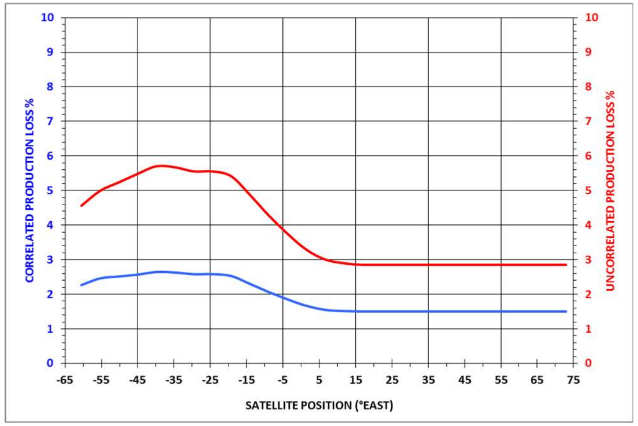
4 main cities; early in adoption



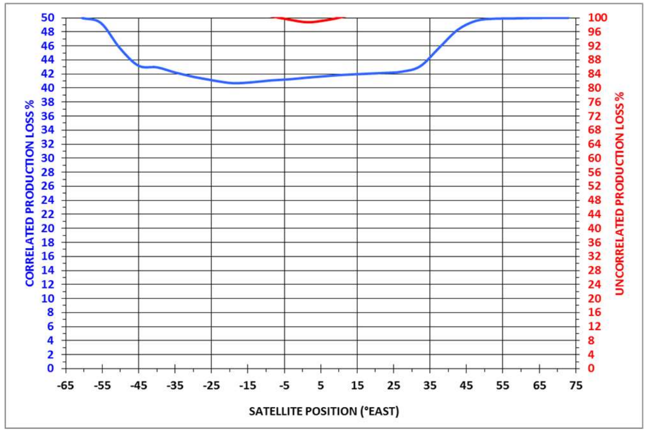
NL-Urbanized; early in adoption



Entire NL (excl 20 km zone); early in adoption



4 main cities; mature in adoption



NL-Urbanized; mature in adoption

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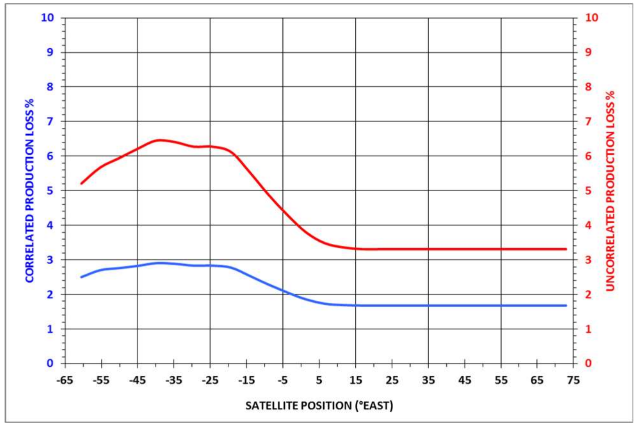
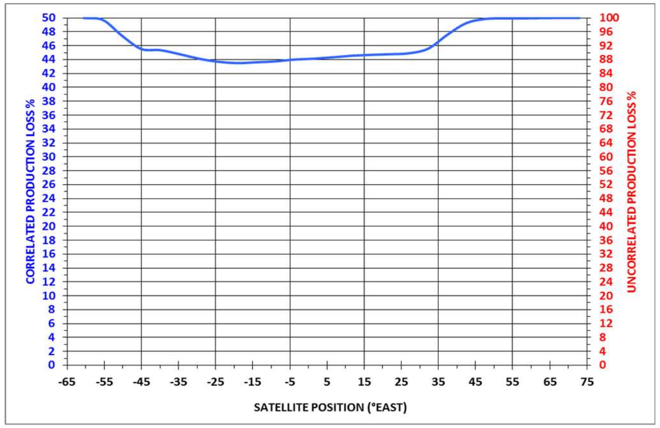


4 cities; evolved phase



NL-Urbanized; evolved phase

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Figure 19: Overview of outcomes of Production Loss calculations for different 5G scenarios taken from our scenario framework.

These diagrams provide us with the following (additional) insights:

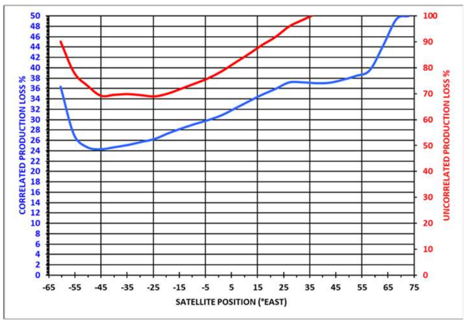
- The hump we see in the diagrams in the left column indicates the contribution of the four largest cities at different stages. If the 5G roll out would remain limited to the four largest cities, then the coexistence problem would be much less severe compared to a nationwide roll out. This takes away any possible prejudice that the “Randstad” would likely be the main contributor, given its demographic and geographic size. The reason why production loss also occurs at other azimuth angles outside the “Randstad sector” is because the largest susceptibility is when the satellite dish is aimed towards the direction of the interference, but at other angles, interference comes in via the side and back lobes of the dish antenna.

- The diagram representing NL-Urbanized at “Early in adoption” stage (first row, middle column) shows the influence of predominantly the city of Groningen on the east side and Leeuwarden on the west side. The reason why for example Groningen comes in so strong is twofold (besides the fact that it is a city): 1) it is very close to Burum (about 23 km) and Burum is very sensitive in the eastern (and western) direction because at those azimuth angles, the dish elevation angle for tracking of geostationary satellites is very low such that wanted signal and interference almost coincide. The situation with Leeuwarden is comparable although this city is further away (30 km) and smaller in size. The contribution of Assen is less prominent because at this azimuth angle the satellite dish has a higher elevation for satellite tracking.

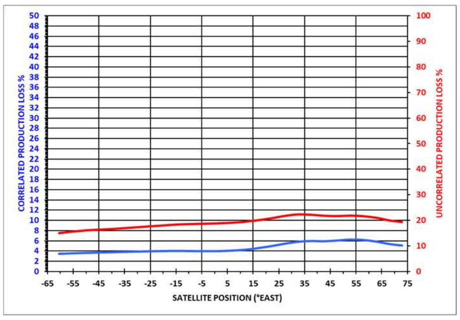
- The diagrams clearly show the impact of the growth of the 5G network and its utilization. It is important to note that the impact of such a change on Burum depends on where it actually happens. In our scenarios we merely extrapolated the current distribution of traffic demand and associated base station densities in the country, except for the ‘Evolved’ phase where we assumed a limited ‘catching up’ effect of network deployment density outside the urbanized areas due to the expected broadening in versatility of uses of 5G based connectivity services in the long term. So, if for example the Eemshaven area in Groningen, would experience an accelerated economic development and subsequent increase in mobile traffic demand over the years, this would be much more impactful compared to a steady continuation in growth of the Brainport area around Eindhoven over the same period.

- A nationwide deployment of 5G is already very impactful in the “Early in adoption” phase. As our model exceeds it’s validity range above 50% (correlated) we did not display the result for the two subsequent phases. This impact is largely due to the presence of 5G (@3.5 GHz) also in the rural parts of the country, and actually approaching Burum quite closely (a 20 km exclusion zone is maintained). We should realize that still by far the largest part of the country is classified as rural.

To illustrate the impact of distance on Production Loss, we show two different plots which were made for a 5G network deployed on the current 1800 MHz site grid using conventional antennas. The absolute PL values should be ignored because the 5G network configuration is a bit different from our framework, but attention should be payed to the difference between the two.



NL-Urbanized, between 20 and 50 km



NL-Urbanized between 50 and 100 km

Figure 20: Comparison of two Production Loss outcomes in two disjunct‘ onion’ rings. First ring is 20-50 km; second ring lies between 50 and 100 km.

This emphasizes the magnitude of the co-existence issue in the northern part of the country (NN-NL).

To illustrate the dominance of 5G deployments in rural parts in terms of impact on Burum, we conducted simulations to assess the production loss per area type: in order to illustrate the differences

1. Type 1: Downtown urban
2. Type 3: Suburban
3. Type 4: Rural

As our Type 2 represents a very small number of PC-4 areas, we left this one out. The exclusion zone that we applied is 50 km in order to take out the strong influence of base stations nearby. The scenario we picked from our framework is S3d (nationwide, mature stage). Although the real world value curve would stay closer to the blue curve (correlated) the incremental effect is very obvious. This implies that reduction of the interference footprint of network deployments in rural areas is at least as important as in urban and suburban areas.

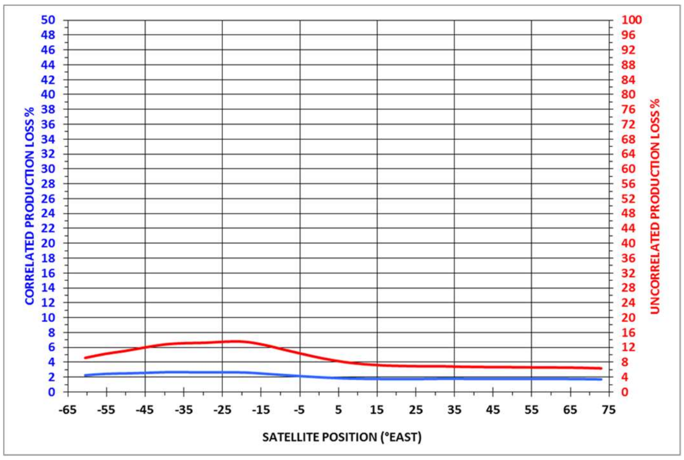


Figure 21: Production loss in case of Type 1 (urban) contributions only

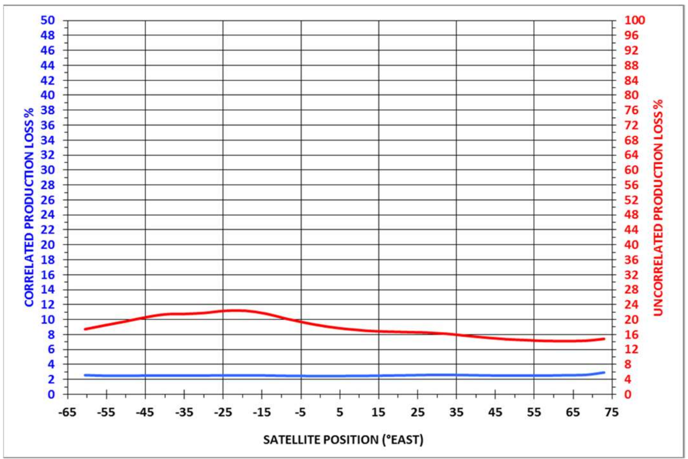


Figure 22: Production loss in case of Type 3 (suburban) contributions only.

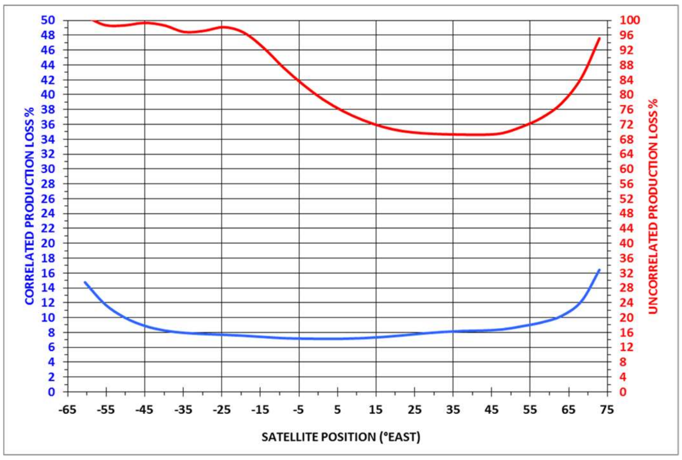


Figure 23: Production loss in case of Type 4 (rural) contributions only.

5.5.2 *Influence of 5G in neighbouring countries*

We need to put these impact figures into the proper perspective when it comes to interference contributions from networks deployed in the Netherlands compared to networks abroad.

In our neighboring countries 5G networks will also start to emerge which may impact the Burum Interception Facility in the same way. Countries like Belgium and France will not pose a great risk based on distances, but the north-west part of Germany as well as Denmark are within the susceptibility region. Countries like Sweden and the UK are fairly remote but trajectories originating there towards Burum are largely overseas so ducting conditions can be more severe than over land.

The clearest and most present risk is Germany which will auction this band in Q1 next year[61]. In 2009 and 2017 we assessed the possible influence of cities in the north-west region of Germany and mid Germany (Ruhrgebiet), assuming full and robust area coverage within municipality borders). The table below shows for a few selected cities in Germany with which Dutch cities they can be compared in terms of production loss contributions.

Table 7 Influence of selected German cities

German city	Comparable to
Leer	Amersfoort, Rotterdam
Emden	Almere, Amsterdam
Duisburg	Nijmegen
Essen	Nijmegen (twice)
Bochum	Nijmegen (slightly worse)
Dortmund	Nijmegen (slightly less)

This table tells us that future 5G deployments in various cities in the Bundeslander Nordrhein-Westfalen and Nedersaksen will also contribute to the total interference level measured at Burum. The Burum Interception system is more susceptible to sources in Nedersaksen but Nordrhein-Westfalen contains the Ruhrgebiet area which is quite substantial in size.

We do not expect 5G network deployments in this frequency band in rural parts of Germany being equally likely as in the Netherlands' because the business case challenge in Germany is much greater than in our country and a roll out obligation for the 3.5 GHz comparable to the 700 MHz is also not applicable. *If* 5G in this band would be deployed also in rural parts, this will contribute to the interference level in Burum.

[61] Source:
https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2018/201800917_5G.html

5.5.3 *Default mitigation: considering a relaxed Production Loss criterion*

The default option for Burum would be to accept a higher Production Loss performance in the presence of 5G networks. In the previous section we have taken the original "Gold" label criterion of 0.0038%.

The table below shows for two other more relaxed PL criteria the equivalent decoupling loss as well as the remaining decoupling loss in case of 5G scenario 3E:

Table 8: Residual mitigation requirement as a function of PL criterion.

PL criterion	Equivalent decoupling loss	Residual mitigation requirement (assuming 5G scenario 3E)
0.0038%	0 dB	65 dB
1% ('Silver')	14 dB	51 dB
10% ("Bronze)[62]	26 dB	39 dB

An assessment of this default mitigation measure on the Burum side has been incorporated in the overview of possible mitigation measures.

The production loss figures used here are so called expected values, i.e. values that would be obtained through averaging over longer periods of time (assuming the scenario is static during that period). Actual production losses can easily vary over short time intervals.

5.5.4 *Mitigation options in Burum*

The following few pages provide an overview of mitigation options which could be considered for application in Burum. Of each measure, we describe various aspects. Their definitions are listed below.

Table 9: Aspects included in the assessment of Burum related mitigation measures

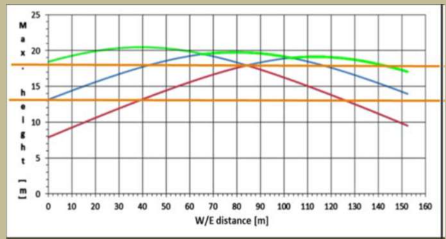
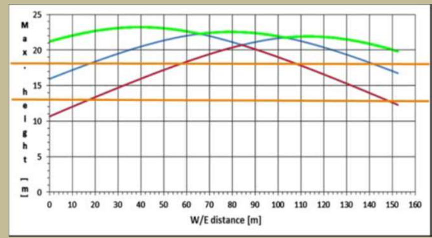
Concept description	Explanation of the mitigation principle
Mitigation effectiveness	Level of radio decoupling that can be expected, generally or under specific conditions. If not quantifiable than at least qualitatively.
Neighbouring country mitigation	The extent to which the measure also helps to mitigate interference from foreign origin.
Reliability	The reliability that the radio decoupling is sustainable or at least predictable.
Technological maturity	The maturity of the enabling technology. Is it still in an R&D stage or do we also see applications with this technology.
Implementation complexity	The complexity involved in engineering to arrive at an operational solution.
Business impact	The impact in terms of reduced capabilities or performance of the system or efforts/costs involved to maintain capabilities or performance at the same level. Only qualitatively.

[62] Production loss figures of this magnitude imply a very serious degradation of the effectiveness of the Burum Interception Facility for intelligence gathering purposes.

The assessment of 5G related mitigation measures according to these criteria is presented below. A subset of these measures are based on Phased Array technology. Annex F contains a more elaborate explanation of the principle and its possibilities.

Measure	**Acceptance higher maximum production loss KPI ("Silver and Bronze")**
Concept description	Accepting a certain maximum technical productivity loss as a consequence of reduced system performance is probably the most difficult mitigation measure to present and discuss. The meaning of this measure is that the actual interception of a certain maximum percentage of interceptable messages is accepted to fail. This is a mitigation measure in its own right, because acceptance of reduced system performance of the one, gives headroom to the other application and vice versa.
Mitigation effectiveness	The mitigation effectiveness is roughly 1 dB per percent point additional productivity loss[63]. Hence, it directly translates into a lowered radio decoupling requirement between the two applications. A certain agreed maximum production loss creates a 'loss' budget which can be spent in different ways[64].
Neighboring country mitigation	Whether this provides mitigation towards foreign interferers is a matter of choice. The agreed 'productivity loss budget' could for example be assigned completely to foreign interference. This means that up to a certain point, the impact of foreign interference is accounted for. As a consequence though, co-existence requirements towards homeland networks need to be very strict. In this way, the instrument would not be used effectively because it targets external (foreign) sources of interference which are not at all responsive to this measure.
Reliability	The relevant reliability aspect here is that a coexistence arrangement may be set up which is based on co-existence criteria. The maximum allowable productivity loss is principally correct but practically not a very useful criterion. If it is to be operationalized as part of a coexistence arrangement, it needs to be translated into a maximum allowable interference level which is measured according to a standardized and transparent protocol. This translation introduces some uncertainty on the Burum side, because there is no deterministic relationship between maximum interference level and production loss[65]. Hence, there is a risk that actual production loss under specific circumstances may exceed the predefined criterion. .
Technological maturity	Not applicable.
Implementation complexity	Not applicable.
Business impact	The business impact for Burum is the fact that an a priori accepted maximum technical production loss which is 'consumed' in this way, introduces the risk of misjudgment in the prioritization of the list of releasable channels. If there is a residual risk that any of the 'ignored' satellite links could contain valuable intelligence information, then the Intelligence gathering process is weakened because of this risk.

[63] This is a nonlinear relationship but the figure mentioned gives an indication.
[64] This is similar to the Carbon dioxide reduction obligation which can be spent in the most (cost) efficient way.
[65] TNO derived from recent C-band satellite signal measurements a statistical distribution of C/(N+I) values of selected incoming signals during a certain time period, from which the relation between interference level and production loss can be derived. The "snapshot" distribution obtained is a reasonable approximation of the true and non-ergodic statistics involved.

Measure	**RF Shielding (RF Screen)**
Concept description	The satellite dishes installed at the Burum facility could be protected against terrestrial interference through the use of an RF shielding screen. The screening method is a known measure, for which either natural or manmade solutions have been applied elsewhere in the world. It is also a ‘dumb’ measure as it does not in any way adjust itself to changing conditions. This is not a disqualifier per se because the type of terrestrial interference we deal with has certain static characteristics. TNO investigated the screen solution in more detail in 2016[66]. Insights and results obtained have been recaptured in this report.
Mitigation effectiveness	A mitigation effectiveness in the order of 10 dB is achievable. The actual effectiveness depends on the geometry of each of the dishes relative to the screen and how the screen itself is designed (particularly the topside design is important). A complicating factor is that effective screening affects the operational degrees of freedom of the dishes. A particular topic is the ability to receive inclined orbit satellites for which the elevation angle can be extremely low. The conclusion of the investigation was that in case of pure horizontal terrestrial interference (see reliability aspect), the screen solution would be viable while maintaining full operational freedom, except for inclined orbit interception.   Diagrams show minimum screen height (orange horizontal lines[67]) and maximum screen height curves (clearance). The green curve assumes a handover from one dish to the next so to maintain clearance over maximum azimuth range. Actual clearance requirement will be between left and right diagram.
Neighbouring country mitigation	A screening solution is most effective in southern directions where the clearance requirement is most relaxed. Dishes pointing either in eastern or in western direction forces lower screen heights to maintain sufficient clearance. This means that this measure does not provide protection from 5G deployments in north-west Germany.
Reliability	Previous investigation raised concern about the reliability of the RF screening measure due to the occurrence of interference arriving at Burum at higher elevation angles (distorted wavefront), causing the interference to ‘fall over’ the screen. This effect was known but not trivial to predict. Reduction of this uncertainty requires height extension (top orange line). We address this type of uncertainty on propagation aspects in this report.
Technological maturity	The technology is quite mature with companies specialized in RF screening materials and designs.
Implementation complexity	The development of an RF screen is not a principal but a practical challenge because effectiveness depends strongly on materials and design aspects. There is environmental impact because of heights involved, although these can be minimized if suitable materials are used. Development and build (including procedures) may take 2 years.
Business impact	Business impact is the deteriorated interception of inclined orbit satellites, at least if 10 dB mitigation is kept as mitigation target. A possible additional impact would be reduced operational freedom if screen height must be chosen such that Burum is forced into the use of handover to maintain sufficient azimuth range.

[66] Source: A.H. van den Ende at al, Investigation into the effectiveness of RF screening to protect satellite reception in Burum”, December 2016.
[67] Bottom orange line is the minimum screen height (13m) in case of horizontal (undistorted) terrestrial interference. Top orange line takes into account non-horizontal incidence of interference.

Measure	**Conventional satellite dish adjustments**
Concept description	The satellite reception dishes in Burum are standard C-Band parabolic antennas which were not particularly designed to mitigate terrestrial interference, beyond the normal rejection of incoming signals outside the antenna's main beam. A factor that comes into play is the necessary operational freedom of each of the dishes, which does not allow optimization of a permanent configuration. This class of measures is scoped to quite straightforward and conventional measures (based on vast amount of research performed in the past[68]) which can be applied to the satellite dishes themselves: 1. Adjustment dish reflector; 2) Larger dish diameter; 3) Multiple feeders and 4) Application offset reflector
Mitigation effectiveness	Ad 1. It is possible to apply reflector edge treatments (often patented) which improve the sidelobe suppression and front-to-back ratio of the antenna gain. Improvements can be realized in the order of at least a few dB. Shaping and choice of material determine the performance. Ad 2. A larger dish antenna increases the antenna aperture and henceforth the directional gain of the main beam compared to other directions. This measure improves the C/(N+I) ratio of the intercepted signal and is effective in all directions. If for example the current 11m dish would be enlarged to 17m brings a directional gain improvement of 3.5 dB. Larger antenna dishes also create more room to apply additional sidelobe suppression measures effectively. Ad 3:. The current dishes and their feeders are designed for maximum gain, but other feeders can be applied which focus more on sidelobe suppression. One important principle that is applied is called edge tapering whereby the illumination of the edge of the dish is lowered which reduces the far field sidelobes, with a relatively small sacrifice in antenna gain in the main lobe. Theoretical results are very promising (>10 dB additional suppression) but the quality of the engineering, design and manufacturing will determine the real result. For example, it is important for the edge tapering to be effective that the blocking of the dish surface is kept to a minimum. Another principle is the concept of hybrid feeders in which a mixture of electromagnetic modes is generated which result in very good sidelobe suppression behavior if properly designed. In case of Burum, we propose to consider a solution with multiple easily switchable feeders (at least up to 4; switching can be done with mirrors; some RF plumbing required to combine the feeds; to be implemented behind the dish). Each individual feeder generates a specific antenna pattern via the dish. At all times, the feeder is selected which provides the best net interception performance (in terms of C/(N+I) for a particular interception task. This solution does not provide the flexibility of a Phased Array Feeder, but allows to handle a few predefined scenarios at a very reasonable cost. Ad 4: The advantage of an offset reflector is that the available aperture of the reflector can be fully used without any illumination blockage, which is not the case with the conventional (existing) solution. As the practical effectiveness of sidelobe suppression measures like tapering is very sensitive to the amount of blockage of the dish, the offset reflector is generally considered as contributing to sidelobe suppression. The benefit is however small when the blinded part of the dish is already small. Hence, the offset solution may become relevant if a sophisticated feeder solution (option 3) cannot be done without increasing the blockage. This needs to be evaluated as part of the solution engineering required. Offset reflectors do not have a very good cross polarization behavior.
Neighboring country mitigation	All measures have in common that they adjust the antenna pattern outside the main beam. The side lobes can be considerably reduced at the expense of an antenna gain reduction, regardless the antenna orientation. This means that these measures also have effect on foreign sources of interference (to the extent that they enter the antenna outside the main beam).
Reliability	These measures are well understood and have a deterministic capability. They have their performance limitations which must be taken into account (e.g. amount of mitigation gain, limitations in performance related to design constraints, etc).
Technological maturity	All solutions are technologically mature and based on extensive research in the past.
Implementation complexity	Ad 1: Adjustment of the dish reflector is of moderate complexity. The edge needs to be engineered with great accuracy. The mounting of the developed solution on the reflector requires temporary decommissioning of the dish, but is not complex in execution. Ad 2: Larger dishes require stronger and higher footage. Additionally, the terrain layout may have to be altered as satellite dishes may block each other's clearance. Ad 3: Current dishes and footage can be reused. Multiple feeders require a special construction to place the feeders and to be able to select feeders. Ad 4: Current dishes will have to be replaced. Footage construction may be reusable. This depends on physical dimensions, weight etc of the optimal dish configuration.
Business impact	Options 1 and 3 do not imply a permanent business impact. Option 2 may result in smaller number of dishes on the site to avoid clearance conflicts.

[68] Relevant sources: USAF, *Interference suppression studies*, RADC-TDR-64-355, October 1964;Collin & Gabel, *Low sidelobe level low-cost earth station antennas for the 12 GHz broadcasting satellite service*, Western Reserve University/NASA, September 1979; Jacavanco, *Reflector Antenna having Sidelobe Suppression Elements*, US Patent 4,631,547, December 1986; Hazdra et al*, Reflector antennas and their feeds*, Czech Technical University Prague, April 2015

Measure	**Phased Array Feeder (PAF) solution**
Concept description	The current feeder of the dish is replaced by a phased array antenna with an array (a panel) of densely spaced elements. The PAF technology allows the generation of a very specific and, if needed, time variant antenna pattern of the feeder of the dish (*primary pattern*), through combining the weighted and phase shifted signal contributions from the individual antenna elements. This resulting field is projected on the large reflector, generating a likewise specific and time variant dish antenna pattern comprising one or multiple beams. The dish antenna diagram can be adjusted by adjusting the weights in the feeder. It allows greater operational flexibility in the antenna pattern of the dish. Agile patterns are possible. The PAF solution exists in a passive and an active variant. Based on performance expectations, only the active variant is relevant here.
Mitigation effectiveness	A phased array feeder solution allows to adjust the antenna pattern to meet specific pattern requirements. It can be applied to improve or optimize the aperture efficiency[69], create nulls at desired angles relative to boresight[70] or increase the sidelobe suppression across a wide angular range. Effectiveness can be in the order of a few dB (increase or reduction of directional gain) and up to 30-40 dB of radiation rejection outside the main lobe in case of nulling, in combination with spatial filtering methods. Which optimization goal should be pursued requires further investigation. Adaptive optimization of the dish antenna pattern in this way is a tradeoff-off between improved interference suppression and degraded noise performance of the front-end (G/T performance).
Neighboring country mitigation	This measure is also aimed at adjusting the antenna pattern such that outside the main beam, antenna gain reductions can be achieved, regardless of the antenna orientation. This means that this measure also has effect on foreign sources of interference (to the extent that they enter the antenna outside the main beam).
Reliability	It is important that the phased array solution serves a clear functional goal (e.g. aperture improvement, electronic scanning & tracking, RFI suppression) to which the design must be tailored. A system that is well designed in this sense, will operate reliably.
Technological maturity	The concept is already in use, for example in satellite based broadcasting. There is continued innovation going on in the area of phased array feeders (cost reductions in electronics, antenna performance trade-offs, smartness and dynamic behavior, higher accuracies in pattern definitions). Each new application poses specific requirements which must be translated into feasible and cost-effective solutions. .
Implementation complexity	Phased array feeder technology originates from space, radar, communications and direct satellite broadcasting application domains. Interest from radio astronomy side is more recent (ASKAP and APERTIF projects). Complexity and cost depend on design and implementation choices, but overall, the implementation complexity and associated costs are quite substantial. With the change in feeder, modifications in the RF/IF chain are required (multiple elements=>multiple signals). Different implementation options exist (complex to fairly straightforward, driven by implementation requirements and cost reduction strategies).This solution has potential for the current facility but may not be deployable on a very short term. An RFI towards industry would have to reveal which technological solutions can be delivered within a few years time which have the best fit to the satellite interception application.
Business impact	There is no a priori negative business impact, but the trade-off between pattern flexibility and reduced front-end sensitivity must be better understood before the net business *impact*, if any, can be evaluated. Also the dimensions of the phased array panel in the feeder may become relatively large (e.g. 80 cm x 80 cm), creating a blockage in the dish pattern. This could be solved using an offset reflector. See also the dish reflector option. A positive impact is the fact that a PAF solution would allow tracking of multiple targets at the same time.

[69] See : M.A.X. Ruppert, *A study on Phase Array Feeds for Paraboloidal Reflector antennas*, Thesis publication, December 2017;Bradley, *Interference mitigation using a focal plane array*, Radio Science, 2005; Nelson and Adediran, *Performance analysis of a patch antenna array feed for a satellite C-band dish antenna*, Journal of selected areas in telecommunications, November 2011; P. Telagarupu et al, *Design and analysis of Parabolic Reflector with High Gain Pencil Beam and Low Side Lobes by Varying Feed*, International Journal Advanced Networking and Applications, 2011

[70] Phased array feeders are reported to be effective to mitigate interference in case of single site astronomy telescopes. See: Ford&Buch, *RFI mitigation techniques in Radio Astronomy*, IEEE/IGARSS, 2014

Measure	**Alternative interception concept (I)**
Concept description	The overarching idea is to add signals from multiple individual antenna elements or antenna systems in a coherent fashion, and to use appropriate and adjustable weight factors in the addition to meet a certain predefined optimization criterion. Such a criterion could be maximization of the gain in the wanted direction and suppression of the gain in the direction an interfering source comes from. The mathematical foundation of this concept is described in Annex F We went over a few different options based on this principle: 1. Using the existing Burum dish constellation (brownfield approach); 2. Development of a new antenna grid (green field approach), on a *single* site; 3. Development of a new antenna grid on *multiple* sites. This paragraph discusses Option 1.
Mitigation effectiveness	Mitigation effectiveness is potentially high (>> 10 dB) in case of singular interferers as the algorithm can impose a null in the direction of the interferer. The RFI mitigation of multiple dominant interferers, let alone an angular dispersed interference 'cloud' is very doubtful. This is due to the constraints of the existing constellation, the required degrees of freedom in interception (in azimuth and elevation) and the dynamics of the interception (target tracking and changes in the composition of the interference). The likeliness that the optimization algorithm will mathematically find any antenna pattern which will meet the criterion is small, meaning nulls cannot be created where needed and grating lobes emerge where they are unwanted. This is mathematically unstable.
Neighboring country mitigation	The measure is conceptually effective to mitigate interference also coming from foreign networks.
Reliability	Due to the mathematical instability described, this method is assessed as being highly unreliable.
Technological maturity	The array concept as described and the signal processing techniques associated are quite well known. It would however require much research to assess more quantitatively the limitations and boundaries of this solution applied to this particular case (not advised due to questionable perspective).
Implementation complexity	Although this solution offers important advantages related to reuse of existing infrastructure, implementation complexity is quite high, particularly on the signal processing side (mainly an R&D effort).
Business impact	The business impact is mainly the unreliability and expected impact on system performance.

Measure	**Alternative interception concept (II)**
Concept description	The overarching idea is to add signals from multiple individual antenna elements or antenna systems in a coherent fashion, and to use appropriate and adjustable weight factors in the addition to meet a certain predefined optimization criterion. Such a criterion could be maximization of the gain in the wanted direction and suppression of the gain in the angle an interfering source comes from. The mathematical foundation of this concept is described in Annex F We went over a few different options based on this principle: 1. Using the existing Burum dish constellation (brownfield approach); 2. Development of a new antenna grid (green field approach), on a *single* site; 3. Development of a new antenna grid on *multiple* sites. This paragraph discusses Option 2. This principle can be applied in two ways, i.e. using large phased array panels or building a grid of smaller satellite dishes (so no reuse of the existing dish configuration).
Mitigation effectiveness	Mitigation effectiveness is potentially very high because the RFI mitigation capability can be implemented by design, so the optimal system design can be determined for the given application and application requirements. The concept allows dynamic mitigation of multiple interfering sources. The performance is limited by the dimensions and antenna density applied to the grid and the technology of the antenna elements. A solution with Phased Array panels would look much like an enlarged version of the active surface applied in APAR[71], and mounted on a footage that provides necessary freedom in azimuth and elevation (and possibly height). Mitigation effectiveness of 50 dB or more will be feasible. A solution with a grid of smaller satellite dishes may have a similar performance. This would have to be investigated.
Neighbouring country mitigation	The measure is conceptually effective to mitigate interference also coming from foreign networks.
Reliability	Due to the fact RFI mitigation is built in by design, performance reliability can be very high.
Technological maturity	The concept as such has a high technological maturity. The APAR system that was developed in the Netherlands indicates the lower bound of the state of the art in this area (already 20 years ago). The concept of a grid of satellite dishes strongly relates to the SKA project (radio astronomy domain) that is planned to be realized.
Implementation complexity	Implementation complexity is very high. Development of a new and fully operational interception system based on these principles would take 5 to 10 years. Using existing off-the-shelf components, this development time may be shortened.
Business impact	There is no a priori business impact envisioned for this solution.

[71] APAR stands for Active Phased Array Radar. This radar system developed by Thales and which is mounted on a frigate has the capability to track multiple targets at the same time through an agile formation of complex antenna diagrams.

Measure	**Alternative interception concept (III)**
Concept description	The overarching idea is to add signals from multiple individual antenna elements or antenna systems in a coherent fashion, and to use appropriate and adjustable weight factors in the addition to meet a certain predefined optimization criterion. Such a criterion could be maximization of the gain in the wanted direction and suppression of the gain in the angle an interfering source comes from. The mathematical foundation of this concept is described in Annex F We went over a few different options based on this principle: 1. Using the existing Burum dish constellation (brownfield approach); 2. Development of a new antenna grid (green field approach), on a *single* site; 3. Development of a new antenna grid on *multiple* sites. This paragraph discusses Option 3.
Mitigation effectiveness	This concept is known in the Radio Astronomy world and is also one of the options mentioned by the ITU-R[72]. In this particular co-existence case, the mitigation effectiveness is doubtful from a principal point of view. The reason is that if active antenna grids would be applied on multiple sites to create a baseline in this way (e.g. Groningen, Zuid-Limburg, Zeeuws Vlaanderen, North Sea), an important boundary condition is probably not met, which is low to very low correlation between the interferences measured at these locations. This is a particular issue that emerges from the nature of 5G-NR in this band, which is based on Time Division Duplex. This imposes a strict synchronization requirement on all base stations in the network, causing the aggregated interference to tbe correlated
Neighboring country mitigation	The measure is conceptually effective to mitigate interference also coming from foreign networks.
Reliability	Due to the fact the aggregated interference will be highly correlated across all antenna sites, the reliability of this measure is uncertain questionable.
Technological maturity	In the Radio Astronomy world there is much experience (R&D and operationally) with this concept. It is however important to note that the target signals (broadband communication signals rather than weak spectral lines) give rise to various new design and performance considerations and likely also various challenges.
Implementation complexity	Implementation complexity is very high. It is not only the multiplication of option 2 (but with relaxation of performance requirements) but also the data processing part is complex. From each site a high bandwidth data flow must be transported over fiber to a centralized location. Signal delay corrections will be needed to ensure coherent addition of signals at the centralized location, which will require substantial data processing and data storage facilities (unless, specific satellite channels are selected for interception).
Business impact	There is no a priori business impact envisioned for this solution.

[72] Source: ITU-R, *Techniques for mitigation of radio frequency interference in astronomy*, ITU-R Report RA.2126-1 (09/2013).

Measure	**Mitigation via signal processing techniques**
Concept description	If either the wanted signal is known (and the remaining part is unknown noise or interference) or the interfering signal is known, signal processing techniques can be applied to discriminate the wanted and unwanted components. In case of Burum, the satellite signals which are intercepted often have known characteristics which does not automatically mean that demodulation can be done with a similar performance as with a cooperative receiver system[73]. This means that recognition of interference components (which emerge above the system's noise floor) is important to achieve successful demodulation, especially at (sub) critical carrier to interference ratios.
	The most promising approach is to be able to apply spatial filtering which means that with the use of antenna technology the wanted signal source is separated from the rest. The existing dish antenna already applies this principle, but the achievable discrimination is not sufficient. If a situation could be created in which two received signal flows would be generated with exactly the same receiver front-end, but with ideal spatial filtering through different antennas, a subtraction algorithm would reduce the interfering component.
	The problem in the case at hand is to achieve a good spatial filtering. There are two different problems: Firstly, we deal with a spatially dispersed interference source (not just a point source but rather a cloud). This aggregated interference enters the dish antenna where each tiny slice of arriving interference is attenuated with a directional gain factor which is specifically associated with the angle of incidence relative to the antenna's boresight. Across the whole azimuth range we have an infinite number of these tiny slices each getting a specific directional gain factor. This means the aggregated interference component of the signal that arrives at the receiver behind the antenna, has been strongly influenced by the antenna diagram of the dish. Any successful subtraction method requires a replica of this received signal, but then without the wanted signal component. This replication cannot be achieved with any other antenna than the one we had in the first place. This would actually mean that we need a second dish+RF chain but one that catches the terrestrial interference but does not contain the wanted satellite signal. This brings us into a circle. We are not at all sure whether a Phased Array Feeder would be helpful here. This is too much of a long shot. The second problem is that Burum deals with satellite signals with low to very low elevation angles. In such cases spatial filtering is not effective because wanted and unwanted signals cannot be spatially separated.
	An alternative approach is to obtain the original interfering signal through an independent channel and subtract it from the signal arriving at the satellite interception receiver. In case of one or a few single base stations, this would be technically feasible, using the principle that is applied in modern mobile networks for local interference cancellation. In our case this is not viable because of the diffuse nature of the aggregated interference coming from multiple base stations along the horizon, nearby as well as further away.
	5G Downlink signals from one network do show very strong correlations in the frequency and time domain due to the time synchronization in the network and the 5G signal structure definition (see Annex B and later in this section).
Mitigation effectiveness	Not applicable
Neighbouring country mitigation	Not applicable
Reliability	Not applicable
Technological maturity	Not applicable
Implementation complexity	Not applicable
Business impact	Not applicable

[73] A cooperative receiver is intrinsically part of an end-to-end communication system. In intelligence gathering (eaves dropping) non cooperative receiver techniques are applied.

Measure	**Mitigation via notch filtering of SSB bursts**
Concept description	The downlink signal of a 5G network has certain characteristics which would allow (time gated) notch filtering of the incoming signal. The timing and subcarrier assignment of the periodical SSB Burst is exactly defined. Each sector sends out its SSB blocks (one per beam, 143 duration s in C-Band) within a 5 ms time interval duration, and with a repetition interval of 20ms. An SSB Block has a particular subcarrier assignment which comprises 20 so called Resource Blocks which equals 7.2 MHz. Hence, this aggregated signal power can be taken out with a narrow band filter, so it does not affect the broadband receiver performance. This could even be done in a time gated fashion if this would be beneficial to the interception process. The other parts of the spectrum in use by the operator carrying user data would not show this ‘heart beat’. .
Mitigation effectiveness	The SSB blocks are expected to enter the Burum receiver system as a relatively strong (narrowband) interferer. If its level would be taken as reference value for the incoming interference in relation to the production loss estimate, then the mitigation requirement we calculate would actually have to be increased with up to 3 dB. We assumed in our calculations that a given DL carrier load would be distributed over all available subcarriers (each subcarrier has an equally likely probability to carry data).
Neighbouring country mitigation	There is a possibility that in order to maintain a high spectrum efficiency value, all 5G networks in the C-band would have to be time synchronized. This is first of all a national matter, but lack of synchronization with foreign networks create interference issues in the border regions. Hence, this would mean that this measure could also be effective to mitigate foreign interference.
Reliability	The reliability of this measure is high.
Technological maturity	A (time gated) notch filter will be developed using well understood RF technology. So, the technology maturity level is high.
Implementation complexity	The application of a (time gated) notch filter is not complex, but should be properly engineered, since it will be inserted in the signal chains.
Business impact	The resource blocks occupied in the 5G signal may coincide with a channel containing an interceptable satellite signal. In that case, demodulation and decoding will probably fail (also without notch filter)

5.5.5 Discussion and subconclusion

Basically all mitigation measures considered including alternative interception solutions will as such not be able to provide the level of isolation (65 dB) needed to be fully protected against 5G networks which resemble the more mature or evolved deployment scenarios from our framework.

The best RFI mitigation performance can be offered with a full phased array concept. This is however a very costly solution which will take at least a decade or so to develop and put into operation. Any decision to turn to such alternative concepts should be carefully considered as part of a vision on future intelligence gathering in the Netherlands targeting satellites.

The screen solution has some uncertainties regarding its effectiveness. The development and placement of an effective screen is not a trivial project. It might provide a 10 dB decoupling gain in the best case situation but also introduces operational limitations. On the basis of our current insights, dish antenna adaptations are more promising.

Signal processing techniques as a mitigation measure in its own right will not work in our view because of the nature of the interference arriving at Burum.

To enable a level of coexistence with 5G until at least five years from the introduction of 5G, including coping with 5G interference coming from German networks, mitigation solutions are preferred which are sufficiently effective and can be realized relatively quickly on the basis of what the facility has to offer today. It appears to us that modifications to the existing dishes, including the feeders offer a good compromise between effectiveness and implementation complexity and they can be realized in time. This measure is however far from sufficient in relation to the single sided mitigation requirement (65 dB).

5.6 Dividing the future mitigation challenge

5.6.1 Division of mitigation responsibilities

Co-existence between the two applications can only be successful if sufficient radio decoupling can be achieved and maintained such that both applications can be exploited with the required performance. When a new application enters a band with existing users the new application is normally expected to take into account existing users. This is also the case now with the introduction of 5G based mobile networks in this band. Our previous analysis has made clear that a single sided mitigation burden (in this case on the side of 5G) is not practically achievable and would henceforth lead to the conclusion that co-existence between both applications is not possible. **TNO determines not** the relative priorities of both applications because that is a governmental-political consideration and decision, but given the debate on his topic it is fair to state that the Burum Interception Facility as well as 5G based mobile networks are both considered important to society. Hence TNO has proposed to adopt a burden sharing approach in this investigation where both applications take their share in the joint mitigation challenge which improves the co-existence perspective. Hence, we have assumed an equal distribution of the total mitigation solution as a useful working point in the analysis. An important consequence of this ‘separation of concerns’ is that with a proper co-existence arrangement, each application can take care of its own mitigation strategy independent from the other.

From these assumptions, new mitigation requirements can easily be derived which have no formal status. The total mitigation requirement is 65 dB in this case, which is a value associated with our scenario S3e. This value should be viewed as a rough estimation of the requirement to cope at least the first five years after the introduction of 5G in the 3.5 GHz band. In order to work with round figures (not suggesting decimal accuracies), we raised the requirement to 66 dB. Hence, both applications need to ‘find’ mitigation measures which each create a radio decoupling of at least 33 dB.

If we isolate the problem of NN-NL and take the 50 km boundary on the basis of our findings reported in section 5.3, the radio decoupling required in Scenario S3e for the remaining part of the Netherlands would be 46 dB. **This leads to a minimum radio decoupling value of 23 dB for each application**. Resolving the situation for NN-NL will impose an additional mitigation requirement. Hence, this split of the co-existence problem does not make it any smaller but allows to consider solutions which fit better to each part.

5.7 Summary assessment of mitigation options

Based on this proposed share of the mitigation burden we can finalize this chapter with a dashboard overview of the mitigation measures which have discussed. We used colors in the dashboard to enable a quick interpretation, however without a scientific reference. They have the following meaning:

(green)	Positively assessed
(amber)	Assessment raised concern or pointed at uncertainties
(red)	Negatively assessed
(grey)	Unknown or don’t care

The following main attributes are taken in the summary: mitigation effectiveness (which incorporates reliability), business impact and *near term feasibility*. The appreciation of mitigation effectiveness depends on whether the measure would provide a substantial contribution to the mitigation requirement (which we assume is 23 dB). The preference to focus on near term feasibility is to get clear whether mitigation solutions can be made available soon enough to handle the co-existence situation. Near term should be interpreted as: realizable within approximately three years from now.

5.7.1 *Overview of 5G related mitigation measures*

	Effectiveness	Business Impact	Feasibility (mid-term)
Exclusion zone (< 50 km)			
Exclusion zone (>50 km)			
Transmission Power reduction			
Antenna related measures (conv)			
Antenna related measures(adaptive)			
Antenna height reduction			
Small cells (capacity)			
Small cells (coverage)			
Traffic related measures			

From this dashboard we see that except for the exclusion zone beyond 50 km, all measures investigated can be considered quite to very effective. The explanation for this counter-intuitive assessment of the effectiveness of exclusion zones (< 50 km and >50 km) is as follows. Referring to the relative flat slope of the concave segment in the diagram in Figure 17, the minimum radio isolation required is little sensitive to the size of the exclusion zone, at least in comparison to the convex segment where this sensitivity is much larger. So, in absolute sense enlarging an exclusion zone increases effectiveness, but we wanted to point out the difference in sensitivity.

In terms of business impact the outcome is mixed. Four out of eight measures do not have an outspoken negative assessment (which does not imply an operator would favor them). All measures except for antenna height reduction are considered feasible.

5.7.2 *Overview of Burum related mitigation measures*

	Effectiveness	Business impact	Feasibility (mid-term)
Relaxed PL criterion			
RF Shielding			
Conventional dish adjustments			
Phased Array Feeder solution			
Alternative Interception concept (I)			
Alternative Interception concept (II)			
Alternative Interception concept (III)			
Signal processing techniques			
Notch filtering			

From this dashboard we see that the assessment of mitigation effectiveness is mixed. Four out of eight measures are considered at least sufficiently effective. The RF shield, the use of an alternative interception concept with the current dishes and the deployment of phase array grids on multiple locations were all accompanied with concerns about mitigation effectiveness. In terms of business impact, the relaxed PL criterion, RF shielding and the first alternative interception concept did induce a clear business impact. In case of the relaxed PL criterion it should be noted that the business impact will obviously be strongly related to the adjusted value of the PL criterion. In terms of feasibility all alternative interception concepts are considered long term developments. Signal processing has ‘don’t cares’ because the effectiveness is negatively appreciated.

6 Perspective on co-existence 5G and Burum

6.1 Introduction

With the insights gained into the possible impact of future 5G networks on the performance of the Burum Interception Facility and vice versa, and into possible ways to mitigate impacts, we address in this chapter the perspective on co-existence on the short term (2019-2022), medium term (2022-2028[74]) and long term (beyond 2028). We present a proposal for a medium term co-existence arrangement which can be taken into consideration in the upcoming policy making process.

6.2 Co-existence perspective on the short term

At the time this study was conducted, a formal date for the auction of 3.5 GHz frequencies was not determined yet, but the year 2022 (about two years after the upcoming auction) was considered realistic. In August that year mobile communication licenses for the 3600-3700 MHz (and subject to HOL008) will also expire. We have assumed that the HOL008 footnote will remain applicable until that date. Until then, local and/or temporary small scale 5G based network deployments could be accommodated in the Netherlands if either:

- they comply with the HOL008 regulation or
- each case specific analysis would reveal that the deployment under consideration is expected to generate a 'negligible' addition to the noise level at the Burum Interception Facility.

The second condition would open up possibilities to allow small scale 5G application experiments/trials in most parts of the Netherlands. What 'negligible' means must be defined, and these case analyses can only be done theoretically (using the models also applied in this study) because short term interference measurements are difficult and also not adequate. Assuming a 'first come first serve' approach, the current PL criterion of 0.0038% for Burum and related increase of the system's noise floor can be used to assess for each successive deployment whether or not the criterion would be violated. The issue with this approach is that a nearby (small scale) 5G deployment could already absorb the entire remaining "interference budget", and henceforth block any initiative arriving later. A better approach would be to predetermine the maximum number of deployments the government would want to accommodate (until the national licenses are issued) and to subsequently assign a fixed interference budget per deployment. With each spectrum permit request, it can be assessed theoretically whether it is expected to stay within its dedicated interference budget. The interference level will depend on the size of the deployment, the technology applied, the capacity utilization level (traffic), the deployment environment and last but not least the distance to Burum.

Such an arrangement would make it possible to ask permit holders to cooperate with specific activities lead by Agentschap Telecom (in cooperation with JSCU) to 'learn' about 5G emissions and subsequent actual interference performances.

[74] We have assumed national licenses for the 3.5 GHz will be auctioned in 2021-2022. the year 2022 is the assumed year 2028 has no formal relevance. It defines the period (2018-2028) which can still be reasonably well predicted (2028 is where the validity of our 5G scenario framework ends). Towards 2030 and beyond, the uncertainties become too large.

These evaluations can be made useful in the validation of theoretical models for interference prediction.

6.3 Co-existence perspective on the medium term

6.3.1 Facilitating co-existence; from the Burum point of view

In the previous chapter, we reported on the possible impact of 5G networks on Burum and vice versa, and we made an inventory and high level assessment of possible mitigation measures.

We pointed out that operators can follow quite different strategies in the roll out of 5G technology. That is the reason why the scenario framework was proposed. This means that in terms of 5G deployment we may see quite different implementations from different operators. As each operator would use its own licensed 5G channel, this means that the Burum Interception Facility may be impacted differently from channel to channel across the whole interception band. What all deployment scenarios will have in common is that time is needed to reach a certain level of utilization of their 5G layer. This means that over time, aggregated interference levels tend to rise across the whole band but with the probability that these levels will be different from channel to channel within the band due to differences in 5G deployment choices.

For Burum this means that it should actually ‘prepare for the worst’ 5G scenario which could have developed within a certain time frame, a time frame which can be overseen. It’s preparation should be given a certain level of robustness across the entire interception band and the time period should be defined during which this level is deemed adequate. As previously stated, this is to a certain extent guess work due to inherent uncertainties in the 5G roll out, but we think a mitigation target in the order of 20 dB (23 dB according to our calculation) should suffice at least during the first five years after the introduction of 5G and maybe longer.

We show again the dashboard we obtained as a result from the mitigation analysis.

	Effectiveness	**Business Impact**	**Feasibility (mid-term)**
Relaxed PL criterion			
RF Shielding			
Conventional dish adjustments			
Phased Array Feeder solution			
Alternative Interception concept (I)			
Alternative Interception concept (II)			
Alternative Interception concept (III)			
Signal processing techniques			
Notch filtering			

Due to the fact this mitigation target is very high to achieve with maximum reuse of the current facility, we want to point out that the target could be much better achievable by combining the implementation of technical measures (with a predictable mitigation performance), with the acceptance of a higher level of the maximum allowable production loss, which is now set at 0.0038%. The government

could consider a mid-term mitigation approach through the planning and execution of a *Mid-Life Upgrade program*. This program would focus on relevant adjustments to the outdoor part (the dishes) of the existing Facility. This program should be given a certain design target which is substantial, relative to the aforementioned 23 dB target. If this upgrade is realized in time, it will provide protection for several years, after which a graceful degradation phase gradually kicks in.
Beyond a certain level of production loss, the C-band Interception system at Burum becomes quite useless in the 3400-3800 MHz band. It is entirely up to the government/JSCU to determine which level of production loss is acceptable in conjunction with the technical measures. If for example this would be set to 1%, then the design target for the Mid-Life Upgrade program with technical measures would be at least 10 dB which was also the mitigation requirement for Burum in conjunction with the HOL008 line. With our current insights into possible mid-term mitigation measures, we are confident that this minimum design target is feasible.

6.3.2 *Facilitating co-existence; from the 5G networks point of view*

If we focus our attention back on the 5G networks and revisit their mitigation potential by looking again at the dashboard of mitigation measures, we can conclude that almost every measure has in itself a relevant level of effectiveness, is technically feasible but also brings a business impact of moderate or substantial size.

	Effectiveness	**Business Impact**	**Feasibility (mid-term)**
Exclusion zone (< 50 km)			
Exclusion zone (>50 km)			
Transmission Power reduction			
Antenna related measures (conv)			
Antenna related measures(adaptive)			
Antenna height reduction			
Small cells (capacity)			
Small cells (coverage)			
Traffic related measures			

What the dashboard does not tell us straight away is that the actual effectiveness of any individual measure in terms of noticeable reduction in aggregated interference level in Burum depends on how large the share is of the interference contribution a particular measure focuses on, relative to the aggregated interference as a whole. If for example the major part of the interference comes from rural parts in the country, then the application of small cells in downtown areas does not help much. Hence, any mitigation strategy a mobile operator could follow should be according to a break down of his entire *interference footprint* and start addressing it from large to small, up to the point that a certain success threshold is achieved. How this strategy looks like in the material sense will be determined by the network layout he has in mind and the expected traffic patterns and forecasts of those patterns. Later in this chapter we discuss how an operator could be enabled to do such an exercise.

It is essential that the interference footprint breakdown is done as part of the infrastructure planning and procurement process because mitigation measures can best be embedded in the network roll out, to avoid disruptive effects during exploitation. If insertion of mitigation measures is considered at the moment at which a certain ceiling in aggregated interference has almost been reached, then this will cause a severe disruption in the network growth process.

A commercial operator wants to spend his “interference budget” wisely which means that mitigation measures are applied where they are most rewarding. This is in urbanized areas because there is clearly more traffic demand and interference mitigation is easier in such areas. This means that operators may get discouraged to aim for nationwide 5G service coverage involving a large rural part of the country, at least in this pioneer band. This discouragement works against 5G policy ambitions regarding nationwide availability of 5G grade services.

In our view and despite the risk of less preferred 5G roll-out scenarios due to calculated choices, the regulator should not prescribe which mitigation measures should be taken where and when, because only the mobile operator himself has the best information, insights and forecasts to decide which mitigation strategy is most preferable or least disruptive. The regulator can impose an interference level ceiling which is clearly defined and measurable and must be obeyed by the network for at least a certain (high) percentage of the time. This ceiling value should be operator agnostic to the extent that all operators would acquire similar licenses. Each operator has to deal with this ceiling in his own way. To an operator, compliance with a ceiling value brings complications because of fluctuations in aggregated interference levels at Burum which are caused by network related behavior (traffic) and atmospheric conditions. We have proposed an interference monitoring solution as part of a Licensed Shared Access framework which addresses these challenges. This will be discussed in section 6.5.

6.3.3 Investigation into possible solutions for the NN-NL situation

As presented in the previous chapter, within the 50 km zone around Burum, the mitigation requirement increases exponentially as the distance to Burum gets shorter. This was identified as a specific problem which we turn back to in this section. There are three directions we have looked at to cope with the situation:

1. Formalize the 50 km exclusion zone for C-band based 5G
2. Ignoring the proposed distinction
3. Spectrum Split between 5G and Burum

6.3.3.1 Formalizing the 50 km exclusion zone for C-band based 5G

An actual exclusion zone of about 50 km would basically replace the current HOL008 demarcation line. It would avoid the additional mitigation burden, in which case the joint mitigation requirement on the basis of our scenario framework would remain 46 dB. The consequence of this rather bold measure is that this entire area (about 14% of the total geographical coverage area), which includes the cities Groningen, Leeuwarden and Assen, would be deprived from an important class of 5G services enabled via the C-band. Although this exclusion zone is already better than the current situation with the HOL008 line, this motivated us to look into other possible solutions which are discussed in the next subsections.

There are three pioneer bands for the introduction of 5G. Eventually, the delivery of 5G services will even be possible via all frequency bands used for mobile communications. So, if in this part of the country 5G services could not be done using the C-band, what about these alternatives?

- Referring to chapter 3, the 700 MHz band is a pioneer band. It provides coverage and very limited capacity. So, only low bandwidth/low capacity type of 5G applications can be supported.
- Again referring to chapter 3, the 26 GHz band is the third pioneer band. This band which facilitates very high capacity connections over relatively short ranges (except for the Fixed Wireless Access application), is as useful in this part of the country as anywhere else. It cannot be seen though as a real alternative for the C-band which provides much better area coverage. It will also take some time before this band will be commercially exploited.
- Other bands than the pioneer bands will support 5G but this will come later and these bands do not have the C-band capacity potential.

In conclusion, the exclusion zone for C-band based 5G services may not be interpreted as a consequential full denial of 5G in this part of the country. However, NN-NL will get retarded, both qualitatively and quantitatively in the delivery of 5G services compared to the rest of the Netherlands.

6.3.3.2 *Ignoring the proposed distinction*

The proposed distinction is ignored, which means that the 46 dB mitigation requirement is set back to 65 dB which is valid in combination with a 20 km exclusion zone. On the basis of equal burden sharing which we have assumed as guiding principle, both applications would have to find mitigation measures which can add up to approximately 33 dB each:

- In case of Burum, this would result in a 19 dB design target instead of 10 dB for the proposed Mid-life Upgrade Program, assuming a 1% maximum PL. At TNO there is substantial uncertainty whether that is feasible without, or even with serious reduction of operational freedom of the Facility. Increasing the maximum PL beyond 1% which is already a factor 260(!) higher than the current norm further increases concerns about the unavailability of the Interception Facility and subsequent risks in terms of intelligence gathering.
- In case of 5G networks, this would result in a 33 dB mitigation requirement. We expect a mobile operator will use a diagram like Figure 17 to make the trade-off between the costs of geographical presence versus the commercial benefits of that presence. If we look into the 50 km zone, we have the cities Groningen, Leeuwarden and Assen, and surrounding rural areas. The biggest contributor to the problem in this areas is Groningen as this city is larger, relatively nearby and east bound which is a direction also of greater operational interest to the JSCU than westbound. Additionally, 5G deployments in the surrounding rural parts within this zone are harder to mitigate due to the openness of the area. So, if the operator does not want to decline from service coverage in cities like Leeuwarden, Groningen and Assen he is forced to find compensation elsewhere. This must then be found mainly in rural areas, also (far) beyond the 50 km zone. Figure 17 basically predicts that in geographical terms this will be very substantial. In other words, The rural parts in three northern provinces may be completely deprived from 5G in this band just to be able to establish service coverage in the three aforementioned cities.

So, in conclusion, co-channel co-existence of the Burum Interception Facility and 5G networks also within the 20-50 km range from Burum, in the studied time frame does not seem to be a realistic option.

6.3.3.3 *Spectrum split; smart option*

The C-band spectrum contains a vast number of satellite downlink frequency assignments. From an intelligence gathering perspective, satellites differ in interest and priority. Additionally, certain assignments may be associated with satellite links which cannot be received at all (permanent or temporarily) with the sensitive equipment in Burum. This would implicate that the C-band, in the perception of the Burum Interception Facility, contains "white spaces" which could be used for terrestrial mobile communications. A ranking in interest and priority of satellite signals which are visible to Burum, may allow for a differentiated tolerance level regarding production loss in the interception process. If we look at "production loss budget" as instrumental to sharing, this would allow Burum to evaluate e.g. on a day-by-day or even more frequently which channels they can (temporarily) ignore and can be conditionally released to mobile networks. If the releasable set of channels is composed in such a way that the channels which are of particular interest or priority are disguised, this may alleviate the confidentiality concerns.

It is thought as a system of active assignments, so without active assignment of a particular frequency channel, this channel cannot be used. On the other hand, the operators must be given assurance that at any time each of the licenses operators gets the total quota assigned according to their license agreement. Hence, the mechanism is not meant to regulate the amount of spectrum available to the participating operators but to regulate the individual channel assignments.

From the viewpoint of the mobile operator, the rationale would be to reduce the exclusion zone from about 50 km back to 20 km, while in return a smaller spectrum space is accepted. Our simulations have indicated that such a reduction is possible while keeping the minimum decoupling loss beyond the reduced exclusion zone at the value of 23 dB. This is made possible through the minimum amount of power suppression (> 30 dB) the NR transmitter needs to achieve at the spectrum channel border[75].

The principle of equal burden sharing may provide a suggestion as to how the spectrum split could be done.

The drawback for the mobile operator is that instantaneous channel bandwidth which is important for eMBB type of services should be such that the 5G service proposition is at least as good (or preferably better) compared to what is possible with 4G. The lower bound of useful 5G spectrum in this band is around 40 MHz. If this would have to be released to 4 operators, the total quota adds up to 160 MHz. If an equal burden sharing would mean an equal split of 400 MHz in two parts, than this would fit. However, from the Burum perspective this potentially (worst case) reduces the system production performance with 40%-50%. Although the interception production value will not be the same across the whole band, the sacrifice may still be very substantial. This should be weighed against the benefit of being able to serve this part of the country with an adequate 5G based services proposition .

A second drawback is that the bandwidth assigned to an operator may not be contiguous but fragmented. The fragmentation does not pose a technical difficulty (intra band carrier aggregation technology), but the spectrum efficiency is reduced

[75] Source: ETSI TS 138 104, V15.2.0 (2018-07), tables 6.6.4.2.1-2 and 6.6.4.2.2.1-2

as each spectrum portion used for mobile communications needs to incorporate guard bands. For example, a 20 MHz 5G channel incorporates 8% guard band spectrum[76].

At third issue is that the C-band is quite heavily occupied with little ‘white space’. Non-interceptable signals would temporarily create grey spaces providing an opportunity to release. What complicates the matter is that modern satellite communication transponders apply sophisticated channel utilization techniques involving also dynamic use of frequency channels. Hence, the C-band band is not so static and spacy as it may seem.

A fourth issue is an issue which JSCU has to face and which is related to the previous which is the challenge to select releasable channels. This is from a human point of view a huge responsibility because of the risk of misjudgment in the prioritization of the list of releasable channels. If there is a residual risk that any of the ‘ignored’ satellite links could contain valuable intelligence information, then the Intelligence gathering process is weakened with potentially severe consequential implications because of this risk.

A fifth drawback or at least point of attention is that the set of channels that can be made available to mobile operators cannot be determined entirely and alone by JSCU. The commercial satellite ground station in Burum (Inmarsat) as well as the military satellite communications nearby will require protection of their operational channels against interference from 5G networks. Although the susceptibility of these systems is much less than the Burum Interception system, we cannot simply assume that this will not introduce additional limitations in the assignment. During this investigation we have not looked into such limitations, but the following can at least be stated. Inmarsat cannot easily switch their feeder links to another subband. The ground station in Lauwersmeer does have this possibility because C-band capacity can be leased in any part of the band. A small exclusion zone would still apply in order to prevent blocking of the receivers.

The sixth issue is that the proposed flexibility requires active communication about channels which can be released. If the portion to be assigned to mobile operators would be relatively small, then an agile assignment algorithm could actually mask or obscure information about relevant target channels for interception. If this portion becomes larger, then the “processing gain” of this masking operation will reduce. A fixed assignment would be a better alternative purely from that point of view.

The conclusion that can be drawn from this investigation is that a spectrum split in order to resolve the precarious situation in the northern part of the Netherlands is a very relevant measure in terms of creating additional radio decoupling, but it comes with many drawbacks. Hence, all things considered we do not see a smart spectrum split as a realistic option.

6.3.3.4 *Fixed spectrum split*

The simpler alternative to a smart spectrum split is to conduct a fixed split. Still there is the need to assess how much spectrum and which parts then should be released. If we adopt the equal burden sharing also here, the spectrum would have to be split in two equal parts. This would be in our view a poor judgement because

[76] Based on ETSI TS 138 104 V15.2.0 (2018-07), page 26, with SCS=30 kHz.

the reward (enlargement of the 5G service area closer to Burum which is relatively small compared to the rest of the Netherlands) weighs against the penalty of losing half of the spectrum window (!) for interception. If for example a 25% split would be taken, the impact on Burum reduces but would provide the 3 or 4 operators only 100 MHz of spectrum in total which have to be shared in 3-4 parts. This is not enough spectrum to deliver mobile network services which can compete with 4G. An alternative to resolve this problem could be the application of full RAN sharing. This means in this case that operators share a single RAN infrastructure (in this part of the country) and combine their limited spectrum resources into one pool. The shared network carries the Mobile Network Codes of all three or four operators, so any mobile terminal with a normal subscription can find his own operator on the shared network. The shared RAN is coupled with each of the individual core networks.

The advantage of this concept is that 5G service propositions using C-band spectrum are possible because there is sufficient spectrum to do so and the set-up is completely transparent to subscribers. There are however also various issues with this set-up:

- The loss of 25% of the interceptable spectrum is still very substantial from an intelligence gathering point of view. The associated Production Loss is of an entirely different order than previously discussed in this report.
- The frequencies in the pool cannot form a contiguous volume because each of the frequency bundles in the pool has an owner. This owner should be able to use this frequency bundle outside the 50 km zone as part of his larger spectrum portion in a seamless way. This automatically means that the bundles will have to be separated. This then brings back the guard band inefficiencies;
- The shared arrangement inhibits operators to compete with their service propositions. Actually they have to agree on a common set of bearer services and associated QoS parameters which apply in this region and on radio network planning aspects. Whether this lack of competition in this part of the country and associated collusion behaviour.is acceptable or not is an economic policy and regulatory matter. The sharing arrangement solution introduces additional complications in the terms and conditions of the spectrum licenses.
- The set-up will introduce service continuity issues, particularly when going from the non-shared part to the shared zone.

Our conclusion here is that the solution is probably viable from a technical point of view (this has not yet been validated with industry) but also brings its own set of issues.

6.3.3.5 Conclusion

The main conclusion is that there is no easy way out here. We have not been able to arrive at a recommended solution for the NN-NL problem, also because various options also generate issues of a non-technical nature. Any decision on this matter requires a more holistic, multidisciplinary consideration. A structured workshop session involving all stakeholders with adequate mandate (including satellite communication providers) could be held in an attempt to find the least problematic compromise which can then be recommended to consider in the upcoming policy making process.

The table below summarizes the considered solutions and their merits, in arbitrary order.

Considered "solution"	**Rationale**	**Drawbacks**
Introduce 50 km exclusion zone	Co-channel operation is considered not possible in this area. Full 3400-3800 MHz band is maintained for interception.	Area within 50 km from Burum may be deprived from a relevant class of 5G services or serious delays will be applicable. Not enough spectrum to introduce 5G services roadmap comparable to the rest of NL.
Ignore the 50 km boundary	Co-channel operation is maintained. The mitigation burden in this area is not separated but included in the overall requirement. Leave it to both applications how to deal with it.	Resulting mitigation requirement as a whole and for each application is considered not feasible. This inclusive approach therefore essentially blocks a solution for the entire co-existence problem.
Smart Spectrum Split	Leverages the 30 dB additional adjacent channel isolation. Make smart use of (temporary) white and grey spaces in the 3400-3800 MHz band.	Various issues: 1.channels not wide enough for competitive 5G proposition 2.fragmented bandwidth assignments 3.complications with white and grey spaces 4.principle difficulty for JSCU to assign releasable channels 5.decisions on releasable channels also concern commercial satcom at Burum 6.active communication is required about (non) available channels which may violate confidentiality rule.
Fixed spectrum split	Leverages the 30 dB additional adjacent channel isolation Fixed split is much simpler than smart split and more spectrum efficient.	Substantial loss of interceptable C-band spectrum => very high production loss and devaluation of Burum for Intelligence gathering. Not enough spectrum for competitive 5G propositions. Full RAN sharing could solve this but introduces other issues.

6.4 Coexistence perspective on the long term

In this investigation there has been much emphasis on the medium term, i.e. covering the next decennium. Given the validity period of licenses for mobile communications, we want to also use the insights gained tin this study to reflect on the long term perspective.

Given the ‘magic triangle’ in 5G which refers to the combination of NR technology, massive MIMO technology and the relatively very attractive characteristics of this band, we expect it will play a pivotal role in the future development of mobile networks worldwide, in Europe and henceforth also in the Netherlands. The forecasted growth in traffic demand which might in the Netherlands be even higher than average in Western Europe, what the recently published ACM figures seem to indicate, forces operators to remain active on spectrum acquisition, densification and technology renewal. Technology upgrades and additional frequencies are seen as solutions to avoid cumbersome densification. Hence, the pressure on utilization of spectrum in this band will certainly grow in the Netherlands as well as in surrounding countries, particularly Germany. In spectrum management terms, the amount of radio decoupling needed is already very serious in the timeframe we have considered **but it will grow even further over time**. We do not know however how fast and whether the characteristics of the interference may also evolve. The mitigation challenge will therefore increase but 1) we do not know how fast and 2) how the influence of Germany develops in the coming years. Hence, a future reconsideration of the whole co-existence situation is deemed necessary.

We have looked into various mitigation techniques on both sides. There is clear potential in various technological solutions to get prepared in time to create an acceptable co-existence situation far into the next decennium. Mitigation techniques which can be realized in time may however not provide sufficient protection past 2030. A long term sustainable co-existence arrangement probably not just needs more of the same but will require, at least partly, different solutions. If only the networks in the Netherlands can be subjected to mitigation and not in Germany, the effectiveness of NL-only mitigation measures will automatically deteriorate. This effect must be taken into account in deriving a long term strategy.

The exploitation of C-band satellite communications also faces growing decoupling requirements, but this is of a different order.

Based on this situation and forecast, we therefore recommend to consider:

- Setting up a co-existence arrangement scoped to the Netherlands, including mitigation measures which can last until far into the next decade;
- Incorporating an evaluation of the entire co-existence situation just before 2030. This evaluation must also be included in the 3.5 GHz licenses to operators;
- Developing a vision on C-band satellite interception in the context of national security and on the way C-band interception could be practiced in the Netherlands involving the methodology as well as the facility on its current location.

6.5 Towards a mid-term co-existence arrangement

In this section we present more concrete proposals which together form a co-existence arrangement that is valid for at least until 2028 and may stay even relevant until after 2030, depending on future developments. This section is split into the following subsections:

1. Co-existence supporting framework: LSA (6.5.1 and 6.5.2)
2. ‘Mitigation by design’ in 5G networks (6.5.3 and 6.5.4)
3. Mid-Life upgrade Burum (6.5.5)
4. Interim evaluation and licensing implications

6.5.1 Co-existence supporting framework: Licensed Shared Access (LSA)

Licensed Shared Access is basically a spectrum management tool under a spectrum licensing regime. It aims at enabling the introduction of new users in a frequency band additional to the incumbent users. The new users get access to the spectrum subject to conditions (regulatory constraints) contained in the licence. The objective of LSA is to ensure guarantees to incumbent users as well as LSA licensees in terms of spectrum access and protection against harmful interference. As such LSA will in principle allow both the incumbent users as well as the LSA licensees to obtain a predictable quality of service. LSA does require a quite close cooperation between both applications.

The LSA concept and associated tools/mechanisms could provide a very useful framework to organize and control the co-existence between Burum and future 5G networks. Agentschap Telecom is also looking into this direction. A dedicated framework could be developed according to the following step by step approach.

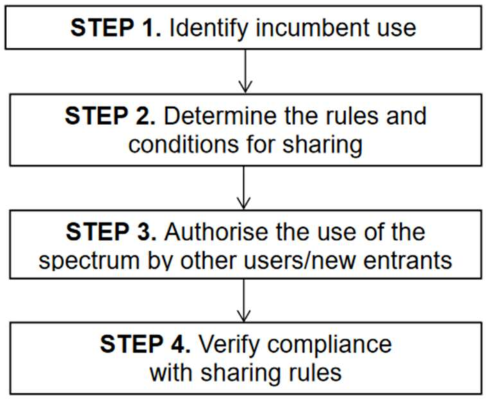


Figure 24: Step by step approach to set up a sharing framework. Source: ECC[77]

In the current project a significant effort is dedicated to the identification of the incumbent use: satellite interception. The technical and operational characteristics of the satellite reception facility have been determined and from that the required protection level has been derived.

An additional step compared to the approach depicted in Figure 24 is that also the 5G network technology and deployment scenarios have been analysed to be able to derive the total aggregate interference that can be expected at the satellite receivers in Burum.

Both elements are required as input for step 2 of the approach ‘determine the rules and conditions for sharing’. At this step the close cooperation between incumbent user, new entrant (5G mobile operator(s)) and the NRA get essential. This is the core of the current project in which several possibilities for sharing are explored. A complicating factor in this co-existence dossier is the confidentiality of the Interception application, which not only reduces transparency but also constrains the shared use of spectrum because by definition information about the channels

[77] Source: ECC Report 254, *Operational guidelines for spectrum sharing to support the implementation of the current ECC framework in the 3600-3800 MHz range*, November 2016

which can or cannot be shared would have to be disclosed to the LSA partners (the mobile operators). We have had this limitation in mind during this investigation.

The LSA framework should at least accommodate the following needs concerning interference management:

1) Interference level monitoring at Burum and subsequent feedback to mobile operators
2) Burum prescribed access to spectrum for mobile as a possible solution to resolve the NN-NL issue

Both will be described in the next section.

6.5.2 Interference management measures under LSA framework

As previously explained in this report, during certain percentages of time the radio propagation loss can and will be significantly lower than average. When no adequate protection measures are taken, during these periods the interference level at Burum may exceed the tolerated ceiling which results in (additional) production loss for Burum. When such excursions can be detected it would be possible to respond timely and adequately e.g. through reduction of emitted power levels in the network.

Measuring and monitoring aggregated interference levels over longer periods of time can also be of interest to mobile operators in order to keep track of their deployment/exploitation and interference footprint balance and anticipate certain adjustments in their network design or dimensioning.

So, the measurement of aggregated interference would serve three purposes:
1. Fulfilment of the regulatory role to monitor compliance to the LSA conditions (particularly on the mobile network side);
2. To provide instrumental feedback to the mobile networks regarding the amount of additional decoupling that needs to be achieved (basically taking a role in EIRP power control) in order to return to the legal situation in case of a threshold override;
3. To provide mobile operators with measured data which allows them to monitor the long term trend, in anticipation of certain adjustments required. This would be a service rather than a formal task.

With respect to the design of such a mechanism, various aspects need specific attention:
- The definition of the boundary or ceiling value of aggregated interference (bandwidth, averaging time, minimum requirement on percentage of the time this ceiling shall not be exceeded);
- The ceiling or boundary value itself. This value (and its definition) should be included in the license, so much care must be put into the determination of this value. The analysis contained in this report may be helpful in the determination of the value by Agentschap Telecom;
- The stability of the feedback mechanism, i.e. to avoid unintended instabilities in the mobile network due to short term fluctuations which trigger the feedback mechanism. Some kind of hysteresis margin would have to be applied;

- The interface specification between the regulatory and operator components in such a set-up.

A possible implementation of this concept has been depicted below, which is inspired by LSA examples known today (see Annex E). The set-up focuses on the immediate alerting but additional functionality can be easily added.

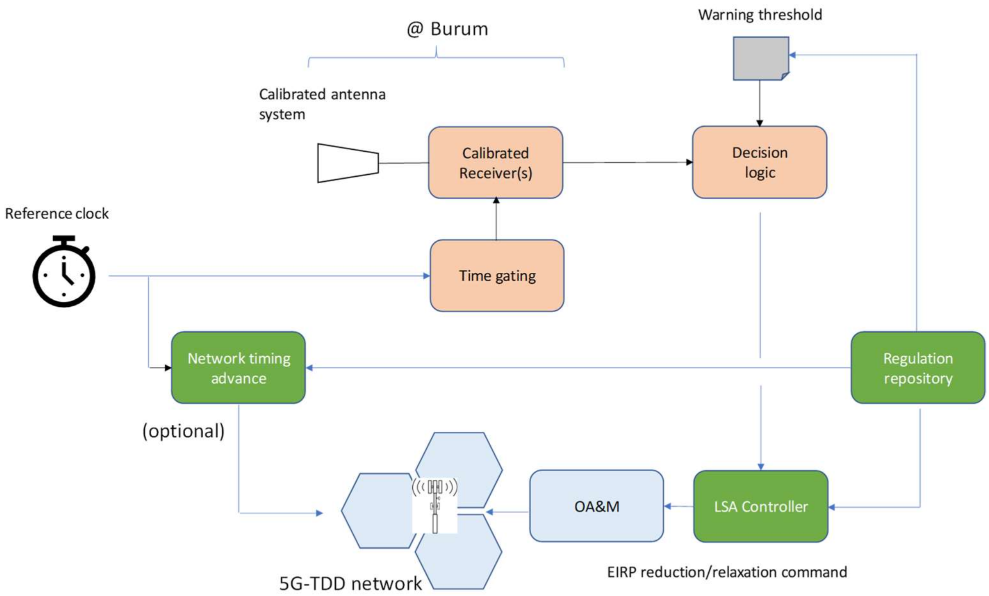


Figure 25: Possible set-up of an interference measurement and alerting system

The set-up as proposed makes use of the fact that 5G networks in this band must be exactly synchronised in order to avoid interference issues. Although the verdict is not out yet how far the synchronisation requirement should go, we made use of the necessity, at least within one network, to have the base stations synchronised. The 5G signal contains repeated synchronisation and broadcast signals on particular sub carrier frequencies at exact time epochs. This is by definition deterministic because mobile terminals must be able to connect to the network in this way.

In the frequency domain these (SSB) signals are contained in a band of 7.8 MHz[78] within each operator's spectrum and they occur in bursts within specified time intervals[79]. The number of these "SSB bands" to be measured equals the number of licensed operators. Using the information about the structure of the signal it can be calculated that these bursts can be successfully integrated within the spectrum band they will be sent, and using time gated integration to achieve a decent signal to noise ratio in the detection. In this way a kind of prewarning can be given using this part of the emitted signals which will reach a higher aggregated value compared to other subcarrier frequencies which are loaded with traffic and will be less correlated. The optional 'time advance' refers to a possibility to allow a gradual clock shift in the network across the whole country to ensure that these bursts all

[78] It should be noted that we had identified the necessity of a notch filter for this band, to protect the Burum Interception receiver.
[79] Source: 3GPP TS 38.211

arrive at Burum at exactly the same time. Whether such a time shift is allowed in a 5G network is questionable due to the very strict synchronisation requirement. The time advance is not strictly necessary to make this work.

The measurement system, comprising a measurement receiver (actually multiple receivers because each receiver is tuned to one SSB band) and antenna should be calibrated and should be located at Burum on a known reference position and reference height. Radio link budget calculations we did have shown that this principle can be applied successfully such that even very remote base stations could be detected under short term favourable propagation conditions. The measurement antenna needs to have sufficient directional gain (20 dB order of magnitude). A directional antenna with a scanning pattern ensures that each bearing within the relevant azimuth range can be measured at full and sufficient gain. An additional advantage of a scanning directional antenna is that it allows angular separation of the incoming interference such that azimuth sectors which have a suspected portion of interference from German networks can be weighted differently compared to other(south bound) sectors. This prevents Dutch operators to get punished for third party contributions.

The regulatory repository contains the conditions for co-existence, the most important one being the threshold value to trigger a warning. A back-off value may be applicable so the threshold value is lower than the legal boundary. That is an implementation decision.

The measurement system will, through the decision logic, produce an alert if the threshold is exceeded. The alert message will be sent to the LSA controller along with supporting data. The LSA controller will submit a message addressed to the OA&M system of the operator to be warned. EIRP control is a feature already existing in contemporary networks so the new element is the interface with the LSA controller. This type of functionality with associated interface standards is emerging with the arrival of LSA solutions. The solution to report back to the operator could also be simplified. The key functionality here is that the information is coded in an agreed format, is sent in time and in a secure way to the right destination.

The EIRP reduction instruction does not need to specify where in the network this reduction should be applied. The alert message only specifies how many dB the EIRP footprint needs to drop. **The operator will determine where and how in the network the reduction is actually carried out.**

6.5.3 ‘Mitigation by design’ in 5G networks

Mobile operators are facing the challenge to build their 5G layer in the 3.5 GHz band in such a way that they can fulfill their commercial ambitions while making sure they are and remain compliant with the co-existence arrangement and meet the interference criterion for the minimum specified percentage of time.

The challenge is twofold:

1. To find a balance between reusing as much of its existing infrastructure as possible, and the need to minimize emissions in the direction of Burum;
2. To know in advance how the interference level at Burum will probably build up over time, as a function of network roll out and utilization.

If the operator, being halfway his exploitation ambition, finds out he has used most of his “interference budget” then the further development of his network is at jeopardy. So, a mobile operator must have a means to predict the interference implications of wide scale as well as small scale deployment choices and of variations in utilization (traffic load) as part of the tactical planning process.

Operators use radio planning tools to predict the (local) signal strength distribution in their network in comparison to the self-interference level induced by the same network. In this way cell edge conditions can be calculated everywhere and improved if needed by adjusting the radio planning in the relevant area. In this way the impact of new sites or adjustments to existing sites can be evaluated prior to installation and commissioning or retrofit operations.

An additional function would be required in such a tool which calculates the EEIRP value of a selected part of the network, much in the same way as we performed in this investigation. Using the P.452 ITU-R model in a standard or calibrated quality, it is possible to assess the contribution of a particular area to the aggregated interference level induced by his network (assuming certain load conditions). This can be done also on a larger scale, i.e. for the network as a whole. The measurement system as part of the LSA framework which we presented in the previous section could provide continuous feedback on interference levels measured and henceforth provides an operator the means to improve the prediction quality at least on the level of his entire network.

A capability like this allows operators to also assess how the EEIRP of a certain area (for example a town) could be minimized by evaluation of different mitigation options which are viable to apply in that situation.

Annex B of this report contains a description of the EEIRP calculation method.

6.5.4 Early warning service for mobile operators

Given the stochastic nature of the aggregated interference, this makes it difficult to mobile operators to anticipate in time. It is in the interest of mobile operators that immediate EIRP alerts can be avoided as much as possible. Hence, we investigated possibilities to predict atmospheric conditions and subsequent deviating propagation conditions and propagation anomalies (ducting).

6.5.4.1 Predictability of propagation conditions

When for the area of interest detailed data about the actual atmosphere is available, an accurate prediction of the propagation loss can be derived for a certain path at a certain moment. Consultation of the KNMI (Koninklijk Nederlands Meteorologisch Instituut) learned that they have weather models available that are able to provide the relevant forecasting data for the atmosphere. TNO therefore requested the KNMI to perform a study whether its weather models would be able to provide forecasting data regarding the prediction of the refractive index in the troposphere, focusing on the lower few hundred meters[80].

Forecasting the propagation losses over a specific path depends on the accuracy of the data in height levels and granularity of the grid. KNMI uses a model called

[80] KNMI, Prediction of atmospheric ducting, August 2018, KNMI-2018/1981

“Harmonie” [operational version 36 and evaluation version 40]. These models characterize the atmosphere in 3D, i.e. aspects like moisture, temperature, interaction between various layers, etc., etc. are simulated. The Dutch version of Harmonie encompasses an area of approximately 2000 by 2000 km centered around the Netherlands. Harmonie is run every 3 hours.

The present version calculates temperature and humidity levels at 65 different heights/air pressures. Compared to the operational version H36, H40 forecasts 8 levels below 200 meters, instead of 6. Earlier versions of Harmonie had even less levels below 200 meters. A high number of forecasting levels provides intrinsic better possibilities for improvement in forecasting the refractivity, especially for UHF and SHF frequencies. Based on temperature and relative humidity a (modified) refractive index pattern versus height may be produced. This data is available on a geographical grid of 2.5 km.

The TERPEM™ propagation package is a tool for the forecasting and analysis of refraction, ducting and terrain effects on radio links and radar systems. It is based on a hybrid models combining parabolic equation and ray-trace techniques. TERPEM is limited to 2 dimensions (2D), meaning that only the effect of straight paths with zero width can be studied.

Based on the atmospheric temperature, relative humidity and pressure profiles, (modified) refractive index pattern versus height can be derived. The refractivity profiles at several points along the path can be imported in the radio propagation model TERPEM.
The propagation path can be characterized and the losses for a given frequency may be calculated. Given the level of accuracy and grid granularity this would be a unique tool. It should be noted that VHF and UHF enthusiasts, like radio amateurs, have been using tools which provide short and medium term “radio weather” forecasts for about a decade. These tools show an indication of the refractive index, but do not show the impact on a specific frequency as the height of the inversion and depth are not taken into account. The accuracy is also limited as only open (free) weather data sources can be used. In spite of these limitations, the provided data has been known to be fairly accurate [81],[82].

Figure 26 shows the path loss predications that were calculated using the sketched approach. This is done for the path between Amsterdam and Burum, for two periods of 48 hours. PL in this diagram means Propagation Loss.

[81] http://www.dxinfocentre.com/tropo_eur.html
[82] https://tropo.f5len.org/forecasts-for-europe/

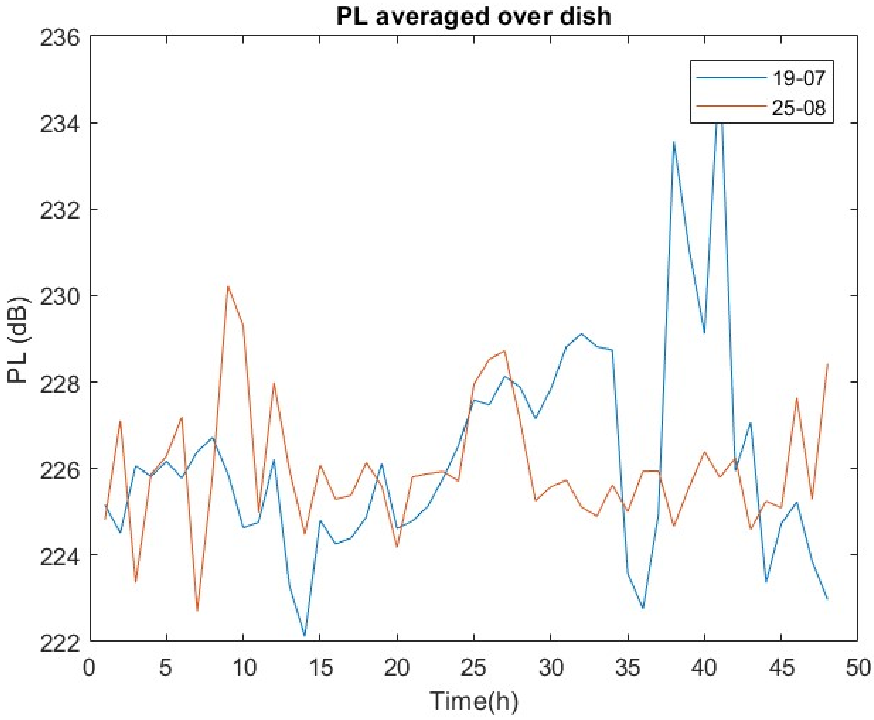


Figure 26 Forecast path losses using Harmonie 40, for 19 + 20 July and 25 + 26 August 2018.

Harmonie has not been used before as a means of providing refractive data of the atmosphere. The initial results however show that the average loss of the standard atmosphere have been predicted well with respect to what is provided by the ITU-R P.452 (see Fig. 9). Anomalies did not appear in the results, although some were expected.

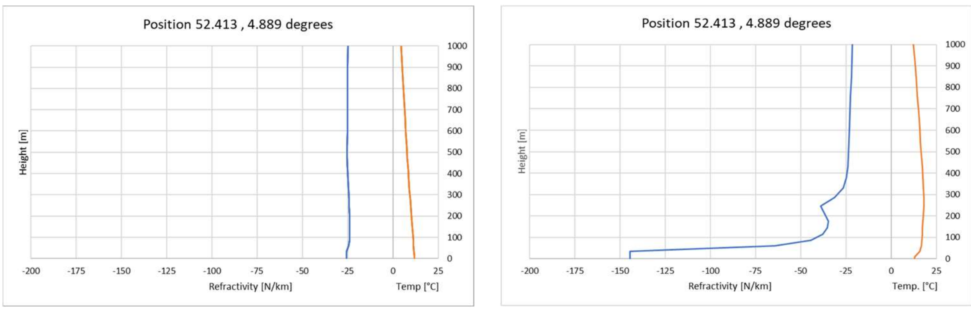


Figure 27 Forecast refractivity profiles for August 25th (left) and July 19th (right).

Shown in Figure 27 are the refractivity indices versus height and the temperature. On July 19th at 04 UTC a pronounced inversion and change in the refractivity can be seen. Further analysis has shown that this was not the case for all the grid points, hence this may have been the reason that no effect was seen on the attenuation losses between Amsterdam and Burum (See also Figure 14).

The integration of weather data (Harmonie) and TERPEM shows promising prospects to become a valuable forecasting tool. Validation tests will have to be performed to verify the results. If the validation is successful, a co-existence arrangement could be established in which the exclusion zone can be reduced to an extent that for instance 99% of the time the interference criterium is met. With the combination of Harmonie and TERPEM the events of anomalies in the atmosphere that lead to significant reduction of the propagation loss can be predicted (similar to weather forecasts the level of certainty decreases with time). This is could be used as an early warning service to operators, either as part of the LSA framework (under Agentschap Telecom responsibility) or as a separate service (public-private initiative).

6.5.5 *Mid-Life Upgrade Burum*

We propose to initiate a Mid-Life Upgrade program for the Burum Interception Facility This program should be given a design target of at least 10 dB mitigation effectiveness. This should be interpreted as the minimum amount of additional radio isolation which has to be imposed on a signal originating from a terrestrial source and arriving at Burum, before its enters the receiver system of the facility just before signal detection. The underlying assumption of the program is that the current Facility is reused to the maximum extent and that it can be realized in three to four years.

The presentation and assessment of possible mitigation measures learnt that the following measures are relevant to consider:

- Conventional dish adjustments
- Phased Array Feeder solution
- RF screening

If we take a closer look at the interception process in Burum, the following conditions can apply within the azimuth sector of interest:
- Interception at low to very low elevation angles whereby the interception is affected by a higher noise level (earth temperature) and additional effects of terrestrial interference entering the main lobe or first side lobe of the dish;
- Interception at higher elevation angles whereby the impact of the earth (earth temperature and terrestrial interference) is reduced.

At the same time, maximization of the operational freedom of each of the dishes of the Facility is an important requirement. This means that each dish must be able to be tasked for any of the possible interception scenarios (no task specialization).

This means that each of the nine dish installations would have to be upgraded in the following way:

- Enlargement of the dish in order to reduce the beam width, increase the directional gain and increase the margin for the application of specific sidelobe suppression measures (such as minimization of relative illumination blockage);
- Upgrade with a multiple feeder solution which allows switching between different dish illumination patterns some of which are optimized for sidelobe suppression (edge tapering). The current double-frequency-band assignment has to be taken into account in the design;

- Additional Sidelobe suppression measures on the dish to the extent they do not disrupt the illumination patterns of each of the feeders;
- Strenghtening of the footage and if needed also its fundament.

The maximum possible enlargement of the dishes is subject to minimum clearance conditions which apply to the current Facility set-up. This means that dishes should not block each other's field of view.

Only if needed, additional RF screening could be applied as a complementary measure. Given the costs of screening, there should be real mitigation benefit of at least 5 or 6 dB. The screening solution is advised to be applied on a per row basis (East-West orientation of each screen in a straight line), with smooth and lowering edges at either end.

The Phased Array Feeder is an interesting concept but the feeder will become fairly large (80x80 cm is a realistic figure). For this reason this (complex) measure is not very suitable for the nine 11m dishes because the relative blockage will be large which is expected to jeopardize the side lobe suppression performance of the main dish. Even in case of enlarged dishes we are reluctant to advise this measure because the enlargement is not substantial and (relative) illumination blockage can be a killer of sidelobe suppression techniques. The application of the PAF concept on the BRM-3 antenna ('it grutte ear') is however quite attractive. It would turn this dish into a very capable and flexible antenna system over a wide azimuth range. If the BRM-3 is equipped with PAF, it will be able to track multiple targets. The larger illumination blockage caused by the PAF solution would not pose a substantial degradation to this dish because the relative blockage stays very small. Additional screening does not make sense for this antenna because of its height. A PAF upgraded BRM-3 antenna would remain fit to purpose also after 2030.

The order of magnitude cost of a Mid-Life Upgrade program along the lines described here is estimated to be 10 MEUR. The realization time is expected to be within the required period except for the PAF solution which may take more time for a full operational implementation.

6.5.6 *Interim evaluation and licensing implications*

Given the inherent uncertainties in this co-existence dossier which relate particularly to the development of 5G as a whole and the utilization of the C-band specifically, both in the Netherlands as well as in surrounding countries, we propose to plan for an evaluation of the entire situation, most preferably before 2030. The agenda for this evaluation would have to be:

Looking back:
- Evaluation of the co-existence arrangement upon 5G networks development in the Netherlands until that date;
- Evaluation of Burum 2.0 until that date and analysis of interference level development;
- Evaluation of the LSA framework;
- Assessment of the state-of-affairs in Germany.

Forward looking:
- Forecast (2030-2040) of 5G developments in the Netherlands and in Germany;

- Vision on the role of C-band satellite interception for intelligence gathering and ways to continue this activity on Dutch soil or elsewhere;
- Possible revision of the co-existence arrangement for the remaining period until the 5G licenses expire.

It is not advisable to introduce two successive license terms each to be initiated through a separate spectrum auction as this would increase the uncertainty operators are facing with respect to the exploitation of 5G in this band. The investments for 5G are such that operators need long term assurance about the availability of spectrum. It is possible to introduce this evaluation during e.g. a 20 years license term *if* it is announced at the time of the auction. The evaluation may not lead to unexpected additional roll-out restrictions or any other limiting conditions, according to the spectrum licensing methodology. Hence, the period following the evaluation has either exactly the same or otherwise relaxed restrictions. From the perspective of Burum this means that the legal protection that will be agreed and which is to be translated into maximum interference levels will remain the same during the entire license period or could reduce as an outcome of the evaluation.

6.6 Wrap-up

Our perception on the co-existence issue, its development and the proposed way to deal with it is depicted below along a timeline 2020-2040.

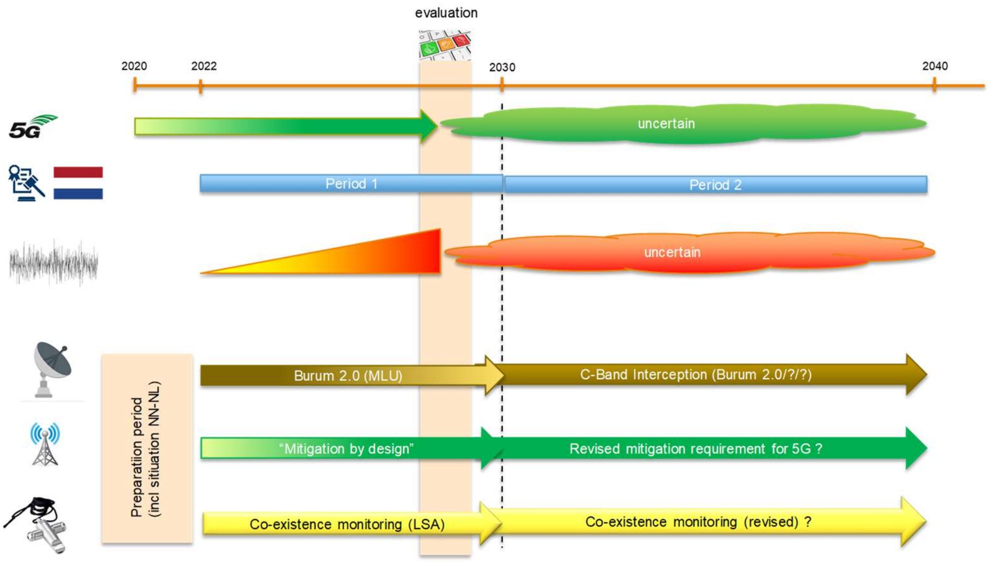


Figure 28: 5G&Burum co-existence issue, its development and proposed actions.

7 Conclusions and recommendations

7.1 Conclusions

The two leading research questions in this investigation were the following:

1. What is the expected radio technical impact of deployed 3GPP standardized 5G networks in the 3.5 GHz band, as assumed to be likely for the Netherlands, upon the performance of the Interception Facility at Burum?

2. Which technically viable measures can be identified to allow 5G network deployments and C-Band Satellite Interception to coexist?

7.1.1 Findings related to Question 1

The performance of the Burum Interception Facility in its current form will be impacted in case public mobile networks would be allowed to use spectrum in the 3400-3800 MHz band. This firstly concerns networks deployed in the Netherlands but Burum is not insensitive to networks abroad using this band, particularly in Germany. Not the existence of these networks, but rather their utilization will induce interference into the receiver systems of the Burum Interception Facility causing loss of interception production/productivity. The magnitude of the impact strongly depends on where, how and how much spectrum in this band will be utilized, and on actual radio propagation conditions. The nature of the entire co-existence problem in the technical sense is strongly stochastic and cannot be fully modelled. Additionally, there is inherent uncertainty regarding deployment choices of individual operators and how mobile networks will evolve in the longer term. This means that conclusions regarding impact, will target the main effects we expect and that margins need to be taken into account in the prediction of the future.

Our expectation is that competing operators will use their 3.5 GHz spectrum license to introduce available 5G technology in their networks (“5G layer”) quickly, driven by traffic capacity demand and by commercial objectives to bring new, 5G enabled service propositions to the market. The 5G technology roll out could be initiated in the cities first, after which this is extended to other parts of the country. However, immediate nationwide roll out is also possible. In our assessment we included various likely options in a time-lined scenario framework, all based on the practice we expect that operators want to use their existing sites infrastructure with additional spectrum before turning towards cumbersome densification. So our framework allows for a limited growth of that infrastructure in the next 10 years.

Given any deployment layout, the actual impact on Burum is largely determined by the level of utilization of the 5G layer in terms of downlink traffic handled. The degree of utilization will grow with an annual factor of 1.4-1.5 which is conservative for the Netherlands and also for this band. **Our assessment is that for *all* scenarios from our framework, the production loss exceeds the norm of 0,0038%** which was formalized for Burum Interception back in 2008. The most mature/evolved scenario from our framework, with an indicative timestamp of 2028 and comprising a nationwide deployment up to 20km distance from Burum, the expected production loss even exceeds the 50%. The impact will obviously increases further, beyond the scope of our assumed 5G scenario framework.

7.1.2 Findings related to Question 2

We have inspected and assessed a range of possible mitigation measures both on the mobile network side as well as the Burum side. Each measure has a certain expected mitigation effectiveness, business impact and readiness/feasibility level. From this assessment we have identified measures which as such we consider as viable, based on their radio decoupling potential and their feasibility for realization or availability, in most cases within a 3 years timeframe from now. Having said that, based on the analysis of the most mature/evolved 5G scenario from our framework, we conclude that we do not see any realistic mitigation strategy through which the 2008-norm for Production Loss could be reached.

Co-existence is possible in largest part of the country for some time to come
It is challenging but technically possible through a combination of measures at both sides, to achieve co-existence between 5G networks and the Burum Interception Facility in the largest part of the country, while keeping Production Loss levels in Burum down to around 1% (order of magnitude) for at least 5-7 years after the introduction of 5G networks in this band which we expect in the Netherlands at around 2021-2022. This assumes that during this period the relative interference contribution from 5G networks in Germany will be clearly less compared the contribution coming from networks on Dutch soil.

Unresolved problem in most northern part of the Netherlands
The situation in the **northern part of the country** is difficult because the joint mitigation requirement increases exponentially when closing in on Burum within approximately 50 km. This would normally call for an exclusion zone of this size. Ignoring this exponential rise in the requirement is not advisable as the resulting joint mitigation requirement cannot be met realistically. **An exclusion zone of this size which includes cities like Groningen, Leeuwarden and Assen, effectively introduces a new geographical split in the Netherlands, albeit much closer to Burum than the current HOL-008 line.** The only effective radio technical solution we see in this band which avoids a permanent exclusion zone of a 50 km radius is to apply a spectrum split which means that the entire 3400-3800 MHz band (ignoring other terrestrial users in this band) would have to be split between the two applications which would reduce the exclusion zone to about 20 km. This spectrum split, either smart or ‘dumb’, raises various issues to both applications, also of a non-technical nature. TNO therefore expects this option is difficult to be accepted by all stakeholders involved as a way forward to reduce the exclusion zone. Non acceptance would make a permanent 50 km exclusion zone basically unavoidable, with the consequence that this part of the country would be provided with 5G services later in time (via other bands), services which will not be comparable to the service propositions elsewhere in the country. Our conclusion is therefore that this exclusion zone issue has remained unresolved in our investigation. We have isolated the matter and the remaining findings presented below ignore the issue.

Proposal to share the mitigation burden
We suggest to share the joint and challenging mitigation requirement equally across both applications, given the fact a great societal importance is attributed to both such very different applications and given the very clear distinction in exploitation goals and responsibilities. In spectrum management terms, both applications then have a co-primary status and carry equal obligations to enable co-existence. The now following findings are based on this suggested principle.

Mitigation on the 5G mobile side
Viable mitigation measures which can be applied beneath this new demarcation line are *on the 5G mobile network side* first of all the application of adaptive antennas together with the application of specific measures also relating to the base station antennas like tilt adjustment, lowering antenna heights and reduction of directional gain in the direction of Burum. Which measure to choose where, should be up to the mobile operator to decide. The use of small cells is commendable where this is possible. The mobile operator will face a resulting penalty in the form of additional densification to maintain a certain targeted quality of service and capacity in the entire network service area. **We expect the mitigation requirement which is in the order of 20 dB will have a clear impact on the costs of 5G network roll out and may also lead to a more selective approach with respect to the roll out of this technology within the Netherlands.**

Mitigation on the Burum side
Viable mitigation measures which can be applied *by Burum* are targeted towards the dishes. TNO considers it feasible to improve the existing conventional satellite dishes such that a mitigation gain at least in the order of 10 dB can be obtained. We also regard a possible concession to the 2008-norm from 0.0038% to for example 1% or any other value as a contribution to the mitigation requirement on the Burum side. In that respect, technical mitigation and relaxed production loss are inter changeable. The major advantage of targeting the dishes is that the facility also becomes less susceptible to interference coming from abroad. This side effect is lacking on the mobile network side. Alternative interception concepts have been considered some of which have a higher mitigation potential. Such alternative is seen as a possible long term solution (beyond 2030) but not suitable to face the mid term interference challenge (next decennium).

Co-existence evaluation needed before 2030
Given the fact that the terms and conditions must be specified in the licenses to be auctioned providing certainty and security to the buyer of the license, the maximum mitigation obligation must be defined as part of the license. Prediction of what the mitigation obligation should be by 2040 is not feasible because this depends entirely on how mobile networks will further evolve into the next decade. Moreover it is very uncertain whether this heavier obligation would be at all bearable for both applications (see paragraph on long term perspective). A pragmatic but important choice is to take 2030 as the next milestone in this respect for which this report provides some early guidance. We therefore propose to set up a co-existence arrangement that is expected to work until the late twenties. By 2030 an evaluation should have taken place at which the entire co-existence situation is reviewed and decisions on this matter are made regarding the next decade (2030-2040) or until the expiration date of the 5G licensed to be submitted, whichever comes first.

Long term perspective on co-existence
The *long term perspective* of this co-existence arrangement is at least very unclear. With the current but modified Facility the expectation is that the growing mitigation pressure in the next decade, also caused by related mobile network developments abroad (particularly Germany), will impose a reconsideration of the co-existence situation. At this point there are too many unknowns to predict now that co-existence possibilities can again be extended until e.g. 2040 through the introduction of alternative interception techniques, on Dutch soil. Full phased array solutions have great potential but are also very costly and require substantial R&D

and engineering effort. The cost-benefit ratio that can be expected in this particular case cannot be reliably predicted with the current knowledge.

7.2 Recommendations

Our recommendations listed below must be seen as valid within the scope of this technical investigation into ways for possible co-existence of both applications. It is fully understood that these recommendations are subject to political evaluation of our conclusions.

7.2.1 Main recommendations

Our main recommendation is to consider the set-up of a mid-term co-existence arrangement that comes into effect immediately after the 3.5 GHz spectrum licenses have been granted and initially lasts until 2030 at the latest. This arrangement assumes a shared mitigation responsibility among both applications and ensures at least the co-existence of the Burum Interception Facility and 5G networks in the Netherlands up to 50 km distance of Burum. It would require a Mid-Life Upgrade of the Burum Interception Facility and the set-up of a Licensed Shared Access (LSA) framework. This framework provides the regulatory/legal setting to ensure proper coexistence between both applications with all stakeholders involved. The LSA framework is executed by Agentschap Telecom and is driven by a per license maximum interference ceiling level which 5G based mobile networks are not allowed to exceed. This interference ceiling must implicitly incorporate the 23 dB mitigation requirement that is imposed on the 5G based mobile networks in this band. This ceiling value and how it is measured should be very clearly defined. Terms and conditions are to be part of the spectrum license conditions.

Tightly coupled to this recommendation is the advice to plan an evaluation of this co-existence arrangement, to be held before 2030. The evaluation is to determine if the arrangement in its chosen form could be prolongated into the next decade or not. This depends largely on how 5G based networks will have developed by that time in the Netherlands and abroad (Germany), how the roadmap for these networks for the next decennium (2030-2040) will look like and also what the vision is on C-band satellite interception in that same period.

Associated with this same recommendation, the following specific recommendations apply:

- TNO recommends the involved Ministries and Agencies (JSCU and AT) to define and develop with involvement at least of Joint Sigint Cyber Unit (JSCU) Burum and the operators **an LSA framework to control the future co-existence between Burum and the national mobile networks**. One essential instrumental part is an Interference Monitoring and Alerting solution as proposed in this report. The second part is the feedback channel towards mobile operators in case the aforementioned ceiling is exceeded (with or without safety margin).

- TNO recommends the involved Ministries and Agencies (JSCU and AT) to use the period until the national licenses are to be auctioned to ***learn*** **from real-life small scale 5G deployments** for which experimental licenses are requested. Allowance of such experiments also above the HOL008 line should be considered as long as sufficient guarantees are put in place to protect Burum from harmful interference. This naturally requires involvement of the JSCU.

- TNO recommends the government to define, budget and execute **a Mid-Life Upgrade program of the Burum Interception Facility (Burum 2.0)** for which this report contains a first high level proposal. If this program can be realized by 2022, the Facility will be ready for the first 5-7 years after the introduction of 5G technology in mobile networks. The design goal for this program is a minimum of 10 dB RFI suppression, while maintaining a large operational freedom of the Interception Facility. The order of magnitude of the costs of the program proposed in this report would is 10 MEUR.

- TNO recommends the government and its internal stakeholders of the Burum Interception Facility to think about the future of Burum as an asset for intelligence gathering based on **C-band satellite signal sources**. Well before 2030, a strategy concerning this specific activity is needed, taking into account mobile network related developments and relevant technologies for interception. During the Burum 2.0 exploitation phase, this strategy should be in execution, in anticipation of an inevitable performance degradation of the Burum Interception Facility towards 2030.

Our second main recommendation to the government is to look at the problem in the Northern part of the Netherlands for which there is no easy way out. Our proposal is to organize a structured and well prepared workshop inviting all stakeholders (including satellite communication providers but also industry) in an attempt to find the least problematic compromise. If this is found this could deliver a recommendation which can be considered in the upcoming policy making process. Other strategies to resolve this should be considered as well. The outcome of this consideration, in whatever form, could have impact on our first main recommendation.

7.2.2 *Auxiliary recommendations*

The following additional recommendations apply:

- TNO recommends MinEZK to obtain insight into the implications of the mitigation requirement suggested in this report on the evolution of mobile networks using 5G technology. Key aspects are the impact on deployment strategies, the additional cost effects and subsequent impact on business cases.
- TNO recommends MinEZK and Agentschap Telecom to consider prolongation of the 3.5 GHz measurement campaign in the coming three years with geographically spread beacons in the 3.5 GHz (e.g. one in each province) with four goals:
    1. To test a Proof of Concept Interference Monitoring solution at Burum, as proposed in this report which is to become part of the LSA framework;
    2. To contribute to an even better understanding of specific propagation effects in this band in the Netherlands area. These effects play a role in this co-existence dossier and are not yet fully understood, causing substantial uncertainty margins in impact assessment and mitigation;
    3. To contribute to the production of scientific propagation data which can be used in an initiative to improve the predictability of special propagation conditions (see next point).

- Mobile operators, Agentschap Telecom, KNMI and TNO could jointly assess how with the current insights obtained in this investigation the prediction of special propagation conditions can be improved and turned into a ‘radio weather forecast’ service mobile operators could make use of.

8 Abbreviations

3GPP	Third Generation Partnership Project
5GIA	5G Infrastructure Association
5G-PPP	5G Public-Private Partnership
ACM	Autoriteit Consument en Markt
AE	Antenna Element
ARIB	Association of Radio Industries and Businesses
BS	Base Station
BWA	Broadband Wireless Access
BWP	Bandwidth Part
C/N	Carrier-to-Noise
DL	Downlink
DSL	Digital Subscriber Line
EC	European Commission
EIRP	Effectively Isotropically Radiated Power
EEIRP	Equivalent EIRP
ETSI	European Telecommunication Standards Institute
eMBB	enhanced Mobile Broadband
FDD	Frequency Division Duplex
FWA	Fixed Wireless Access
GA I&V	Geïntegreerde Aanwijzing Inlichtingen & Veiligheid
gNB	Base Station in 5G network
GSA	Global mobile Suppliers Association
GSMA	GSM Association
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IF	Intermediate Frequency
IMO	International Maritime Organisation
IMT	International Mobile Telecommunications
IoT	Internet of Things
ISD	Inter-Site Distance
ITU	International Telecommunication Union
JSCU	Joint Sigint Cyber Unit
KNMI	Koninklijk Nederlands Meteorologisch Instituut
KPI	Key Performance Indicator
LNA	Low Noise Amplifier
LSA	Licensed Shared Access
LTE	Long Term Evolution
M2M	Machine-to-Machine
MIMO	Multiple Input Multiple Output (antenna)
MVNO	Mobile Virtual Network Operator
mMTC	massive Machine Type Communications
NCTV	Nationaal Coördinator Terrorismebestrijding en Veiligheid
NGMN	Next Generation Mobile Networks
NN-NL	North-North part of the Netherlands
NR	New Radio
OA&M	Operations, Administration and Maintenance
OFDM	Orthogonal Frequency Division Modulation

PAF	Phased Array Feeder
PAPR	Peak-to-Average Power Ratio
PC-4	Postcode-4 level area
PRB	Physical Resource Block
PSS	Primary Synchronisation Signal
RAN	Radio Access Network
RF	Radio Frequency
RFI	Radio Frequency Interference
RP	Reference Point
RSPG	Radio Spectrum Policy Group
SGS	Satellite Ground Station
SHF	Super High Frequency
SSB	Signal Synchronisation Block
SSS	Secundary Synchronisation Signal
TDD	Time Division Duplex
TT&C	Telemetry, Tracking and Command
UE	User Equipment
UHD	Ultra High Definition
UL	Uplink
UMTS	Universal Mobile Telecommunication System
URLLC	Ultra Reliable Low Latency Communications
VR	Virtual Reality
WLL	Wireless Local Loop

A Additional information concerning 5G

A.1 5G development requires a worldwide ecosystem

The complexity of 5G concepts and technology, in areas of radio technology, electronics and software addressing network and terminal requirements is so large that it requires the perspective on the largest possible market scale in order to get developed, produced and deployed. To the extent that the previous generation could still afford regional developments markets, this is with 5G and beyond no longer the case. In this section we elaborate on the organizations which only form the core of this ecosystem as it includes a vast and growing amount of commercial companies.

The ITU and 3GPP are the two global organizations with different mandates but working closely together since the eighties of the last century to shape the vision and materialize and evaluate the standards for global mobile communication systems. The ITU formulates the vision (IMT, IMT Advanced and now IMT-2020) and defines the requirements. The 3GPP organization (Third Generation Partnership Project) develops the associated specifications in subsequent releases. The ITU IMT documents also play an important role in the international spectrum harmonization process. Although the nature of the IMT framework allows the existence of multiple (regional) standards which comply to these requirements, the fact is that 3GPP, which is actually a group of 7 regional collaborating SDOs including ETSI) has become the dominant umbrella SDO with a true global reach. ETSI adopts and regionalizes the global 3GPP specifications for the European market. In the past 3GPP2 also existed alongside 3GPP but with LTE becoming the successor of 3GPP2 CDMA technology, the role of 3GPP2 came to an end.

3GPP works on the incorporation of the IMT-2020 requirements into their standards. 3GPP is an organization that is strongly tied to the telecommunication industries and to user organizations. These are channeled through almost 20 market representation partners such as GSMA, GSA and NGMN. The nature of 5G implies also a stronger involvement of the verticals communities in the standardization process. Particularly interesting in the context of 5G and its European dimension is 5GIA (IA: Infrastructure Association), also acting as market representation partner. The 5GIA is the private part of the European public-private partnership 5G-PPP, a partnership between a large consortium of European ICT industries and the European Commission. The 5G-PPP programme (erected end 2013) resides under H2020 and is targeting research, innovation and 5G trials in EU member states.

A.2 5G trials, standardization and deployment roadmap

In this study it is crucial to have an insight into the roadmap and time planning concerning the worldwide introduction of 5G based mobile networks. This will be the topic of this section using the picture below; showing the different types of activities related to 5G from initiatives (bottom) up to actual deployment (top).

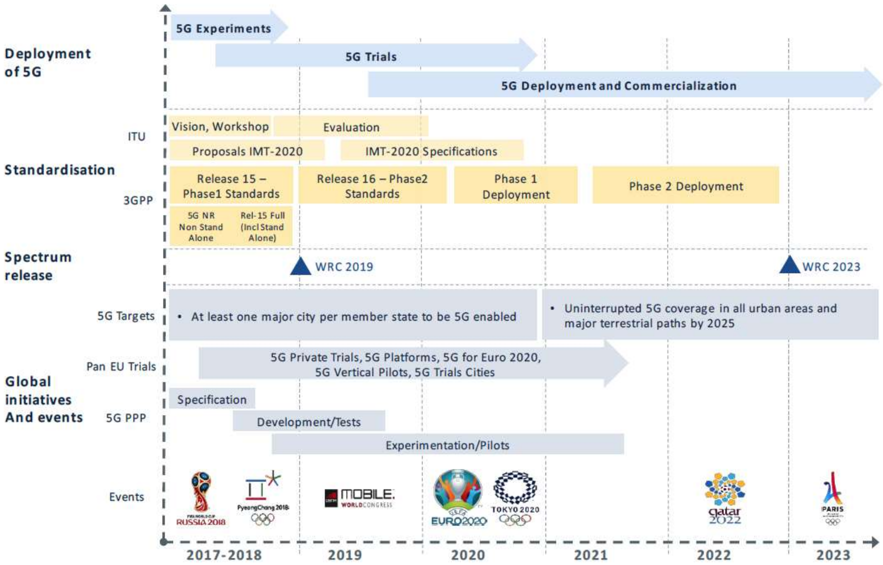


Figure A.1: Simplified overview of international activities in 5G. Source: DotEcon and Axon[83]

A.2.1 *Trials*

The number of 5G trials in preparation and being conducted is growing. On the 5G-PPP website a up-to-date list of European publicly announced 5G trials and 5G initiatives can be found[84]. In the Netherlands, two trials are relevant to mention, i.e. 5Groningen and EURO2020 in Amsterdam ArenA. In the Nordic & Baltic countries 5G city trials are taking place in Kongsberg (Telenor), Helsinki (Telia), Stockholm (Telia) and Talinn (Telia). These trials will actually continue into 2020/2021. The same goes on in Italy, In the US, trials are announced and/or executed by Verizon and AT&T involving Fixed Wireless Access and Direct TV services. In Asia, South Korea has performed trials in Pyun Cheong during the 2018 Winter Olympics and in Japan DoCoMo will conduct 5G trials during the Olympics in 2020.

The trial phase is important because 5G technology comprises various new aspects that require operational evaluation before networks become ready for commercial exploitation. As 5G will demonstrate functional development also after the first “5G Phase 1 Release”, the period during which trials are done will continue also after Phase 1 commercialization kicks in.

A.2.2 *Standardization*

Standardization work on 5G in 3GPP started in 2015 with studies into 5G requirements. The study took inspiration from a large number of whitepapers from e.g. NGMN, 5G-PPP, the Chinese IMT2020 project, 4G Americas, the GSMA and the Japanese standardization development organization ARIB. At the same time the ITU developed their vision on IMT-2020. Other groups in 3GPP, on radio access network or network architecture all followed with initial studies within the 3GPP Release 14 time frame.

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[83] DotEcon and Axon: Study of Implications of 5G deployments on Future Business Models, BEREC 2017/02/NP3, March 2018.
[84] https://5g-ppp.eu/5g-trials-2/

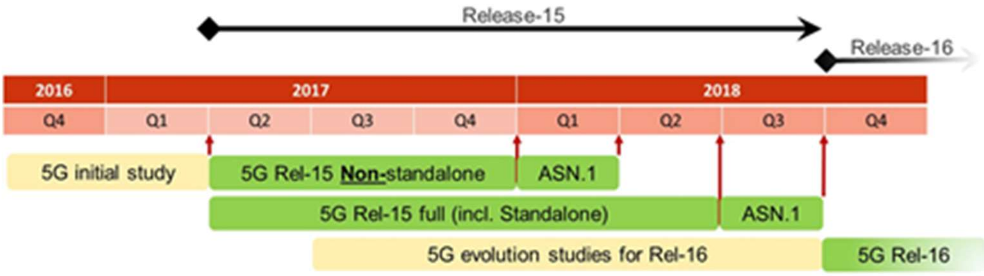


Figure A.2: 3GPP time plan for 5G

3GPP Release 15 is the first release containing specifications. A first 'non-standalone' version released in December 2017 only contains radio interface specifications that can be deployed together with an existing 4G core network. The first full 5G Phase 1 specifications, including specifications of a new 5G core network were finalized in June 2018. Release 16 covers 5G Phase 2 and is expected to be ready in July 2019. Typically 2 years after a Release, mobile devices and networks compliant to that standard are deployed, so by 2020 we can expect the first fully 3GPP compliant deployments to emerge. 5G systems advertised and/or deployed to date are actually pre-standard solutions or non-stand alone solutions. Release 15 covers mainly eMBB type of services, while Release 16 covers all three service types.

4G evolution will not be discussed in this report, but we will suffice with the remark that during a certain period of time 4G and 5G technologies will go hand in hand. The aim of industry is to allow incumbent operators to gradually evolve from 4G into 5G over time rather than getting forced into big bang scenarios. We expect UMTS (3G) to be fully phased out relatively soon. GSM may stay longer as 2G services are still widely in use, e.g. in M2M applications.

A.2.3 Deployment initiatives and expectations

The year of 2019 is generally considered as the launch year for 5G in the world, although the EC is targeting trials in 2018 and commercial deployment (at least one city) in 2020, so there is a tendency to move quickly. For Europe the following announcements are worthwhile to mention (without pretending to be complete):

- Nordic & Baltic regions: Telenor and Telia will both launch on national scales in 2020, following city trials (see previous section on trials and next section on example deployment)
- Italy : 5G small cells deployments in city Torino and in country San Marino in North Italy (2017-2020); Full 5G Coverage in Bari and Matera in South Italy in 2019
- Deutsche Telekom will introduce 5G in its entire footprint from 2020. It has awarded Ericsson in 2017 with a contract to retrofit current RAN network with multi standard radio (5G ready).
- Orange launches national 5G network in phases between 2020 and 2022.

The expected focus at introduction will be on eMBB type of services in the most demanding areas (urban zones). Besides urban areas also major transport paths may be targeted; they are at least promoted by the EC[85].

The diagram below shows the forecast about future 5G deployments that is published by the GSA. The diagram clearly shows that 5G does not replace 4G but is introduced in parallel. During the first 5 years of 5G, the evolution in LTE Advanced deployment is substantial and flattens after 2025.

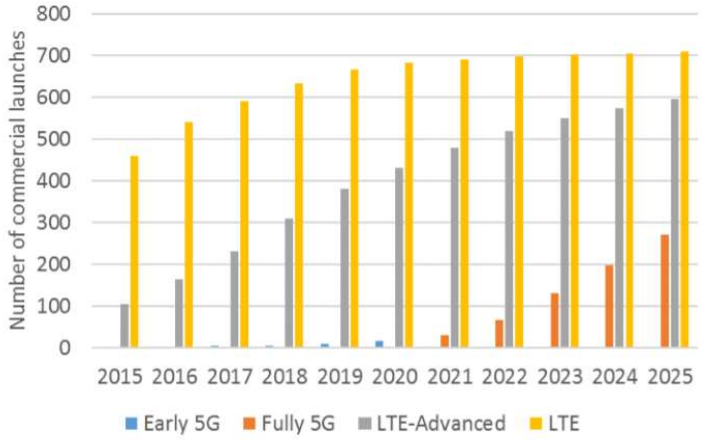


Figure A.3: Future roll out of LTE, LTE-Advanced and 5G as expected by GSA. Source: GSA.

The conclusion can be drawn that in Europe, the launch of early 5G deployments commences before 2020 while national 5G networks will emerge in the 2020-2025 timeframe.

[85] Sources : EC 5G Actions, Creating a Gigabit society, ADL for Vodafone, 2017.

B Characterisation of 5G Downlink signal

Although the influence of uplink emissions of user terminals cannot be entirely ignored, the dominant contribution comes from downlink signals sent by 5G base stations in the 3.5 GHz band. Hence, a certain understanding of the features of 5G Downlink signals is relevant. The information contained in this appendix is derived from various publications on the 5G signal structure. For a more in depth treatment, the reader is advised to inspect these references.

Although the 5G signal structure is inherited from its predecessor 4G, it has various improvements. The 5G Physical Layer design goals were[86]:

- Higher Spectral Efficiency
- Lower in-band and Out-of-band emissions
- Enabling asynchronous multiple access
- Lower power consumption
- Lower implementation complexity

Additionally, The 5G waveform had to be able support an unprecedented wide range of use cases with associated performance requirements. In addition the targeted deployment, topology and spectrum configuration flexibilities of 5G had to be incorporated in the design.

In 5G the ‘always on’ nature of Downlink Control data transmissions of LTE has been reviewed. In case of macro cells serving relatively large numbers of users, the overhead of these channels is limited but that is not the case for small cells. The relatively limited average user traffic in small cells due to their much smaller coverage area compared to macro cells, would result in a high overhead factor and energy consumption. Secondly, ‘always on’ signals create stronger interference conditions which have to be mitigated resulting in lower use data rates. In effect they reduce the system’s spectral efficiency. Hence, in the design of 5G, minimization of ‘always on’ signals has been a priority.

[86] Source: Qualcomm, 5G Waveform and Multiple Access Techniques, November 2015

	IMT-Advanced	IMT-2020
Peak Data Rate	DL: 1 Gbps UL: 0.05 Gbps	DL: 20 Gbps UL: 10 Gbps
User Experienced Data Rate	10 Mbps	100 Mbps
Spectrum Efficiency	1 (normalized)	3X over IMT-Advanced
Peak Spectral Efficiency	DL: 15 bps/Hz UL: 6.75 bps/Hz	DL: 30 bps/Hz UL: 15 bps/Hz
Average Spectral Efficiency		DL eMBB indoor: 9 bps/Hz DL eMBB urban: 7.8 bps/Hz DL eMBB rural: 3.3 bps/Hz UL eMBB indoor: 6.75 bps/Hz UL eMBB urban: 5.4 bps/Hz UL eMBB rural: 1.6 bps/Hz
Mobility	350 km/h	500 km/h
User Plane Latency	10 msec	1 msec
Connection Density	100 thousand devices/sq.km.	1 million devices sq./km.
Network Energy Efficiency	1 (normalized)	100X over IMT-Advanced
Area Traffic Capacity	0.1 Mbps/sq. m.	10 Mbps/sq. m. (hot spots)
Bandwidth	Up to 20 MHz/radio channel (up to 100 MHz aggregated)	Up to 1 GHz (single or multipole RF carriers)

Rysavy Research, 2017 White Paper

Figure B.1: Technical performance requirements of IMT-2020 compared to IMT-Advanced

B.1 Signal structure in Frequency-Time domain

The signal structure as depicted below is defined both in the frequency and time domain. We list here its main features

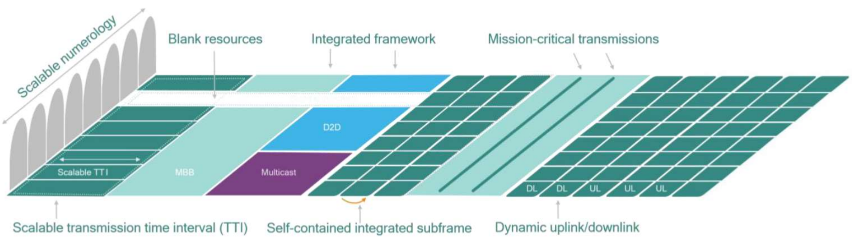


Figure B.2: 5G Signal structure (with main features) in frequency and time domain. Source: Qualcomm

Subcarrier spacing and subframe related through scaling factor: the 5G signal allows multiple subcarrier spacings (in LTE this is fixed) which makes it possible to use the signal structure over a wide frequency range. In the 3.5 GHz band subchannel spacings of 15 kHz and 30 kHz are applied. The subcarrier spacing and the subframe duration are related. As the subcarrier spacing (15 kHz, 30 kHz, 60 kHz, etc) goes up, the duration of time slots shrinks by the same scaling factor. This linkage makes it possible to align/synchronize downlink and uplink transmission in a 5G network deployment quite easily, which is necessary in a Time Division Duplex arrangement to avoid inter symbol interference.

Organisation in the time domain: slots
A radio frame in a 5G signal has a duration of 10 ms and contains by definition 10 subframes of 1 ms. This is exactly compatible with LTE which allows easy interworking with LTE on resource and transmission scheduling. Hence, down to the subframe level the durations at frame and subframe level are fixed. What varies with the numerology, is the number of slots per subframe:

Subchannel spacing	**Nr of slots per subframe**	**Slot duration**
15 kHz	1 slot	1 ms
30 kHz	2 slots	500 μs
60 kHz	4 slots	250 μs
120 kHz	8 slots	125 μs

In all cases a time slot contains 14 OFDM symbols, so the symbol duration scales opposite to the subcarrier spacing. Hence, 5G downlink transmissions in the 3.5 GHz band will apply two possible time slot durations, i.e. 1 ms and 500 μs. A slot can contain downlink data, uplink data or both which is determined on symbol level. The standard supports 62 different slot formats (e.g. downlink centric, uplink centric and various other arrangements).

5G defines one deeper layer in this hierarchy which are minislots which contain a smaller number of OFDM symbols. This will not be further discussed here.

Organisation in the spectrum domain: Physical Resource Blocks (PRBs)

A Physical Resource Block is a group of 12 contiguous subcarriers. The minimum number supported is 24 and the maximum number is 275 (until 240 kHz spacing). The numerology then logically determines the minimum and maximum bandwidth:

Subchannel spacing	**Min. Bandwidth**	**Max. Bandwidth**
15 kHz	4.32 MHz	49.5 MHz
30 kHz	8.64 MHz	99 MHz
60 kHz	17.28 MHz	198 MHz
120 kHz	34.56 MHz	396 MHz

Hence, in the 3.5 GHz band the maximum bandwidth supported is 99 MHz. Considering the existence of guard bands, the net bandwidth utilisation will be lower (92% for LTE in 2.6 GHz as reported by NGMN[87]).

In this way, the frequency and time domain span up a resource grid with a resource element as the smallest unit.

[87] Source: NGMN Alliance, Test and Technology Building Block, technical report, June 2017

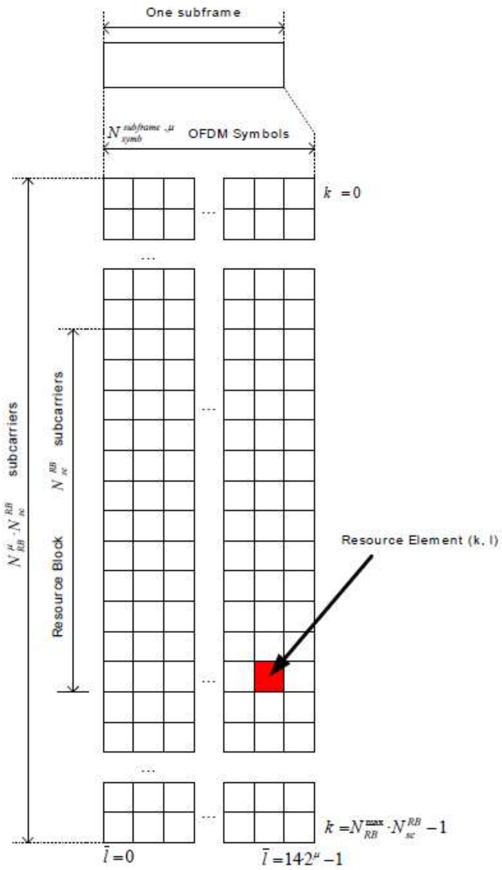


Figure B.3: 5G Resource grid. Source: Keytech

The goal now is to understand better how the resource grid will be used. Although there is a large configuration flexibility, we will highlight the parts in the Downlink signal in an operational network which are fixed.

Downlink Control Data

For synchronisation and access purposes, the downlink carries various control channels:

- PSS: Primary Synchronisation Signal
- SSS: Secundary Synchronisation Signal
- PBCH: Primary Broadcastin CHannel

The SS, SSS, and PBCH channels are basically always on by default (but can be switched off by the network) and are contained in the so called SS Blocks (SSBs) of which the mapping on the 5G resource grid is exactly defined. Each beam accommodated by a TRxP has its own SSB. In time, the set of successive SSB's (one for each beam) are sent in bursts, together within a fixed time interval of 5 ms and with a fixed repetition period of 20 ms (default value). This repetition is expected to create clear periodical patterns, especially if the default value of 20 ms is kept, as all gNBs of one 5G network will be synchronised in time and this is independent from the amount of user data that is being sent to UEs. Within the 5ms time period, either 5 slots or 10 slots exist in case of 3.5 GHz band transmissions, whereby each time slot has two SSB blocks.

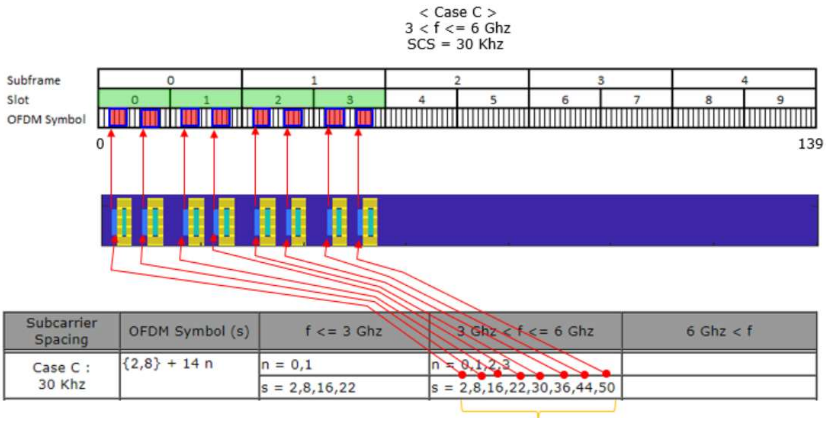


Figure B.4: Allocation of SS Blocks in the time slot structure. Case depicted is for a subcarrier spacing of 30 kHz. One of the two options with two symbols time gap is depicted here, Source: Sharetechnote.com

Spectrum wise, SSBs can be found at different frequency locations. For the 3.5 GHz band, there are 8 different allowed frequency locations, which need not to be aligned with Physical Resource Blocks.

Concept of Bandwidth Parts

The concept of Bandwidth Parts (BWP) makes it possible to offer connected UE's the bandwidth which matches the UE's bandwidth requirements and its transceiver/front-end capabilities. It is likely for example that in the first years of 5G services, there will be terminals capable to handle the full system bandwidth (and being able to consume the maximum peak rates) while others still have more conventional capabilities. This spectrum allocation process can be done in a more efficient way compared to the existing Carrier Aggregation method, although CA is still also possible with 5G.

A 5G Carrier may contain multiple Bandwidth Parts to serve multiple UE's but also individual UEs with multiple RF chains[88]. A UE may adjust his current Bandwidth Part, in the context of data rate and energy management or decide, on the fly, for a complete shift in transmission frequency which introduces a transition time interval of max. 200 μs (intra-band) up to 900 μs (inter-band).

The ability to adjust a 5G carrier to individual UE needs, makes the operation of the Downlink signal more UE specific than cell specific, which is the case with LTE. This implies that a 5G network's behaviour in the downlink is strongly dependent on UE related factors, much more than is the case with LTE.

[88] Source: Intel, NR Wide Bandwith Operations, IEEE Communications Magazine on Key Technologies for 5G, Final Manuscript, December 2017.

B.2 Peak-to-Average Power Ratio

The 5G DL signal has a conventional Multi Carrier Cyclic Prefix OFDM (CP-OFDM) with WOLA (Weighted OverLap and Add) signal modulation format.

CP-OFDM is known for its high spectral efficiency and easy integration with MIMO but has a relatively poor energy efficiency (source: Qualcomm). The signal has a high Peak-to-Average Power Ratio (PAPR) despite the Cyclic Prefix, which means that the signal in the time domain can have high amplitude excursions compared to the average amplitude. With the accumulation of multiple DL signal components arriving at the interception receiver, this effect could be amplified in case of constructive superposition of these signal components.

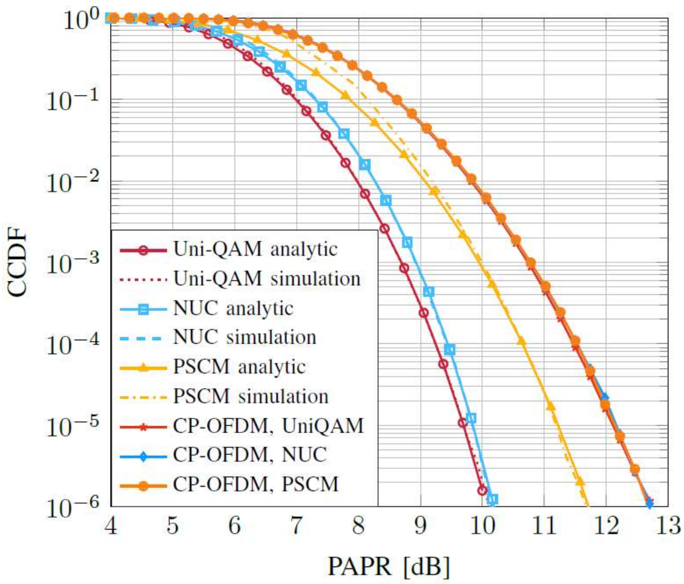


Figure B.5: The Complementary Cumulative Distribution function for various modulation schemes, including CP-OFDM in three different shaping variants. Source: Kakavas et al[89].

[89] Source: A. Kakavas et al, On the PAPR characteristics of DFTs-OFDM with Geometric and Probabibilistic Constellation Shaping, 5G Xhaul Project,

C Impact assessment approach and underlying results

C.1 Approach

A more detailed list of activities and data structures produced is as follows:

- Studies into the interference potential of emissions from 5G based radio access networks have been conducted for different geo types (urban, suburban and rural). These studies resulted in a library of so called normalized Equivalent ERIP profiles for different 5G deployment models and different geo types. For this purpose a ray tracing propagation tool WinProp has been used, together with a clutter database provided by KPN. Measurements have been conducted in Amsterdam and Gouda on operational networks active in the 2.6 GHz band, in order to validate this propagation tool for this band. This led to the trimming of parameters in our 3.5 GHz calculations. The use of measurement data from the 2.6 GHz band for calibration was considered acceptable considering the level of accuracy of the entire methodology.
- A Postcode 4 level (PC-4) library has been created containing all relevant attributes of each PC-4 area taken from CBS and other sources. This postcode level was considered a good compromise between geographical accuracy, coherence in radio propagation behavior and data size. We developed and added a dedicated geo type classification, for this particular use, which is based on building height statistics and percentage of the area with buildings coverage.
- A database has been created of Postcode level 4 (PC-4) areas in the Netherlands with an Equivalent EIRP value for each PC-4 area, depending on its geotype and 5G network deployment model chosen for that geo type. The database also incorporates data on actual site densities which we obtained from the full Antenna Register which was made available to TNO for the purpose of this study. Our fictive operator had available the average number of sites available to one operator, per PC-4 area. It is important to clarify that the resulting 5G deployment on a local level is not tailored in detail according to predicted traffic demand patterns. Current figures about site density per postcode area have been used to obtain a realistic representation of current geographical differences in traffic demand.
- A 5G scenario database has been created, allowing us to define, shape and store any 5G wide area scenario including options to insert radio decoupling factors associated with certain mitigation measures. The 5G scenario database is linked to the aforementioned databases.
- A tool already existing at TNO to model the behavior of the Burum Interception system has been modified and extended. This allowed the calculation of aggregated interference levels entering the Burum receiver systems (via the dishes), for each of the 5G scenarios defined and modelled. The modelling of the production loss calculation was left unchanged, but measurements have been conducted in Burum during this investigation to update signal interception statistics. These statistics are used to assess productivity loss as a function of changes of the noise + interference level entering the Interception receiver. The Burum model incorporates all parameters of the satellite dish constellation of

the Facility, in order to obtain a realistic estimate of interferers and assess the effect of certain mitigation measures.

C.2 PC Area classification

Below, the resulting CDF curves are depicted obtained from 25 different sample PC-4 areas.

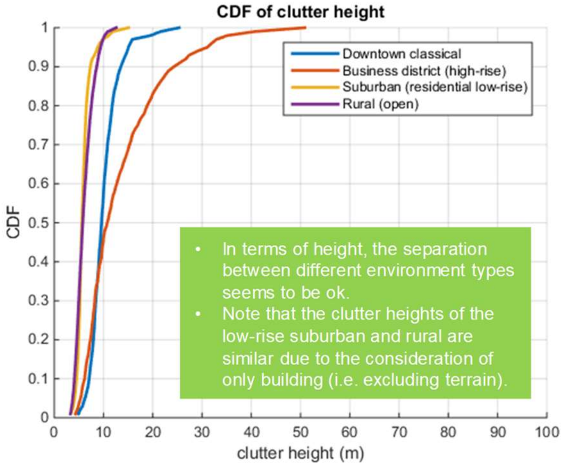


Figure C.1: Resulting CDF's of clutter height for each of the geotypes

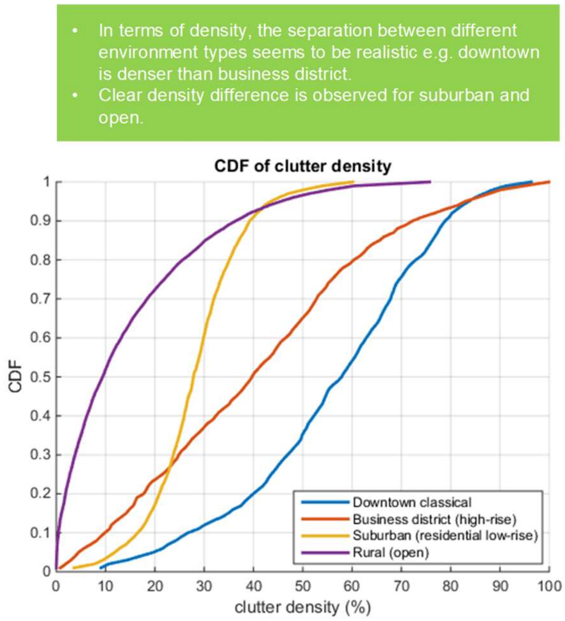


Figure C.2: Resulting CDF's of clutter density for each of the geotypes

C.3 Deployment models

The following three deployment models have been used:

Code	ISD's	Antenna features
Ma_1	500m	Heights: 3m, 6m, 12m, 25m (default) - 3 sector gNBs (baseline) - mMIMO (MC Simulations) Applied in PC-4 areas with geotype "downtown classical" and "business district"
Ma_2	1.000m	Height: 25m - 3 sector gNBs - mMIMO (MC Simulations) Applied in PC-4 areas with geotype "suburban"
Ma_3	1.732m	Antenna height: 35m (default), 50m (high) or 75m (very high) - 3 sector gNBs - mMIMO (MC Simulations) Applied in PC-4 areas with geotype "rural"

C.4 Approach and results Area studies

C.4.1 Approach

We consider a certain confined area as a point source from the perspective of Burum. The granularity we chose in this study is PC-4. Each point source is seen as a fictive transmitter with a certain Equivalent EIRP. The EEIRP calculation for all geotype classified PC-4 areas in the Netherlands is done by selecting a set of (smaller) study areas for each geotype for which the propagation is analysed in detail and an EEIRP is determined. These values are used to derive the EEIRP value of actual PC-4 areas of the same geotype, through straightforward scaling. This section discusses how these Area studies have been analysed.

The principle idea of the Area studies we conducted in this project is depicted below where downtown Zoetermeer is taken as an example.

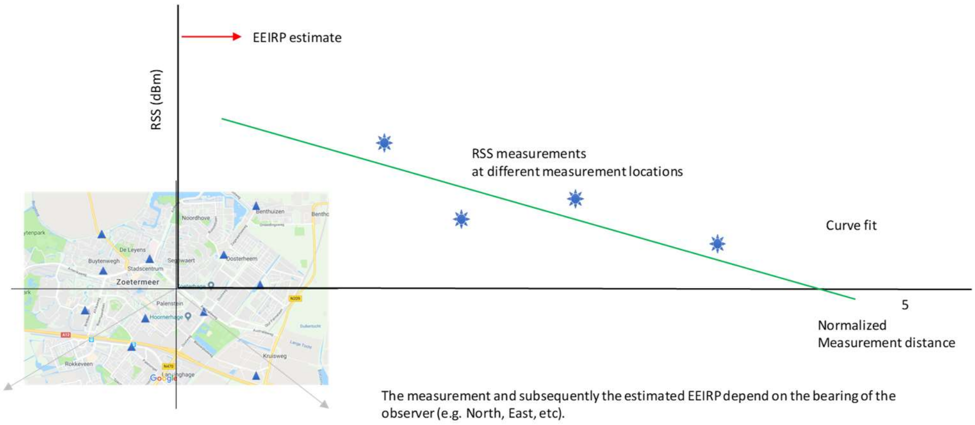


Figure C.3: Deployment in Zoetermeer and measured signal strengths at observation points outside this area in void space. EEIRP is determined by imposing free space loss conditions and conducting a curve fit accordingly.

A certain confined area of a certain geotype with sufficiently homogenous features is selected. In this confined area a deployment model is applied from the table above. In our radio propagation tool, the sites are not projected on actual buildings but on open streets where we can easily vary our antenna height without introducing 3D conflicts. At each experiment all sites are given an identical height value. After projecting all base stations with proper ISD's on the area, a polar raster of observation points is defined, but with all points well outside this confined built up area, where the space is made void and free space loss conditions apply. These observation or reference points have exactly the same antenna height as the base stations within the built-up area. In this way we are able at each observation point to capture the horizontal components of all the active base station emissions. At a given bearing in the polar grid we select two or three distances. This allows us to conduct a linear curve fit (in the logarithmic domain) in order to determine via extrapolation, the EIRP value of a fictive emitter positioned at the centre of our area of investigation that would have caused the same received signal strength values at the consecutive observation distances. With the curve fit we impose the free space propagation loss model. All EEIRP values obtained in this way along 7 different bearings. These values (in dBm) were averaged linearly to obtain an average EEIRP value for the area under investigation. The reason for taking EEIRP samples along different bearings is because we want to be able to apply this "template" wherever in the Netherlands, agnostic to the actual bearing to Burum. The law of large numbers tells us that we will make a certain mistake for each specific area but with the whole set of PC-4 areas these errors will average out.

The figure below shows an example of an actual area study where BS and observation heights equal 12m. On the left hand side the propagation prediction result is shown, summed over all sites (obtained via ray tracing) and on the right hand side the curve fit results. The outcome for this simulation was an average EEIRP of 29.3 dBm with a standard deviation of 2.8 dB.

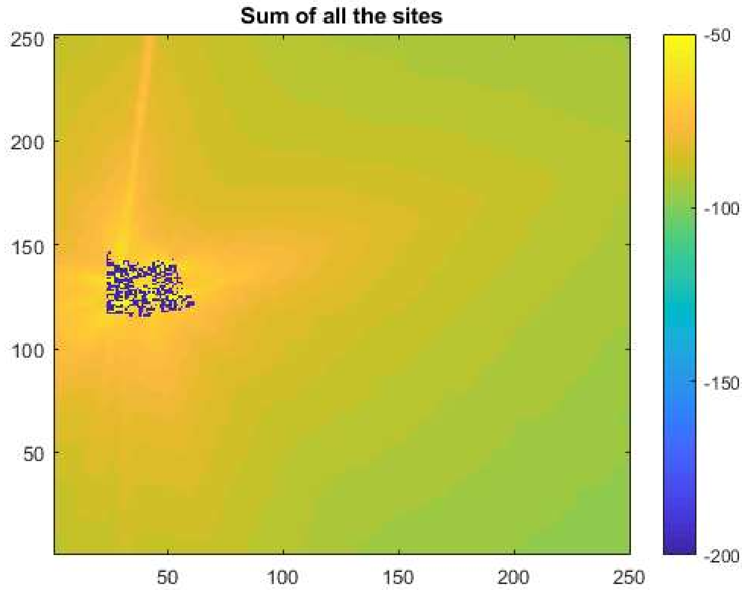


Figure C.4: Result of aggergated received signal strength around the confined built-up area

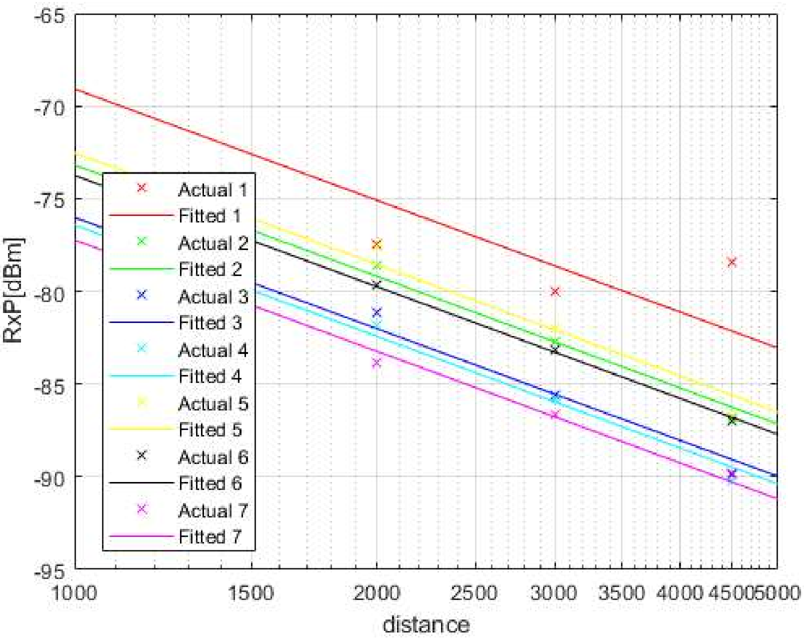


Figure C.5: Corresponding curve fit results

C.4.2 *EEIRP results Type I (downtown classical)*

Area Type	PC4	Tx height (m)	ISD (m)	Site density per km2	Tx power per sector (W)	Tilt (deg)	Mean EEIRP (dBm)	Sigma EEIRP (dB)
1	1017 (Amsterdam) 1.3 km2	3	500	4.6	10	0	17.18	3.74
		6	500	4.6	10	1	26.03	4.00
		12	500	4.6	10	2	29.36	4.29
		25	500	4.6	10	4	40.26	2.31
	9712 (Groningen) 0.84 km2	3	500	4.6	10	0	20.42	4.04
		6	500	4.6	10	1	25.28	4.13
		12	500	4.6	10	2	31.90	3.05
		25	500	4.6	10	4	39.73	2.01
	6221 (Maastricht) 1.4 km2	3	500	4.6	10	0	18.22	3.52
		6	500	4.6	10	1	25.54	3.30
		12	500	4.6	10	2	31.82	4.80
		25	500	4.6	10	4	39.64	3.54

Note: these results were based on 10W transmit power per sector. Scaling is applied to arrive at targeted EIRP values.

C.4.3 *EEIRP Results Type II (Business district)*

Area Type	PC4	Tx height (m)	ISD (m)	Site density per km2	Tx power per sector (W)	Tilt (deg)	Mean EEIRP (dBm)	Sigma EEIRP (dB)
2	1082 (Amsterdam) 1.22 km2	3	500	4.6	10	0	15.65	7.27
		6	500	4.6	10	1	29.43	4.81
		12	500	4.6	10	2	34.81	2.98
		25	500	4.6	10	4	39.33	2.37
	3014 (Rotterdam) 0.57 km2	3	500	4.6	10	0	10.32	11.40
		6	500	4.6	10	1	24.56	6.36
		12	500	4.6	10	2	30.67	4.24
		25	500	4.6	10	4	30.08	2.15
	2521 (Den Haag) 0.97 km2	3	500	4.6	10	0	18.02	6.93
		6	500	4.6	10	1	26.03	4.93
		12	500	4.6	10	2	29.62	4.42
		25	500	4.6	10	4	36.50	2.90

Note: these results were based on 10W transmit power per sector. Scaling is applied to arrive at targeted EIRP values.

C.4.4 *EEIRP Type III Results (Suburban)*

PC4	Total area (sq km)	Tx height (m)	ISD (m)	Site density per km2	Number of sites	Tilt (deg)	Mean EEIRP (dBm)	Standard deviation (dB)
3044 (Rotterdam)	2.04	25	1000	1.15	2	2	46.18	2.31
5022 (Tilburg)	2.6				3		47.73	2.02
9728 (Groningen)	4.35				5		49.87	2.02

Note: these results were based on 10W transmit power per sector. Scaling is applied to arrive at targeted EIRP values.

C.4.5 EEIRP Type IV Results (Rural)

<table>
<tr><th>PC4</th><th>Total area (sq km)</th><th>Tx height (m)</th><th>ISD (m)</th><th>Site density per km2</th><th>Number of sites</th><th>Tilt (deg)</th><th>Mean EEIRP (dBm)</th><th>Sigma EEIRP (dB)</th></tr>
<tr><td rowspan="3">2641,2643,2645 (Pijnacker)</td><td rowspan="3">29.65</td><td>35</td><td rowspan="6">1732</td><td rowspan="6">0.4</td><td rowspan="3">12</td><td>2</td><td>62.45</td><td>1.65</td></tr>
<tr><td>50</td><td>3</td><td>59.67</td><td>1.98</td></tr>
<tr><td>75</td><td>4</td><td>57.6</td><td>1.74</td></tr>
<tr><td rowspan="3">8411 (Heerenveen)</td><td rowspan="3">17.07</td><td>35</td><td rowspan="3">7</td><td>2</td><td>60.01</td><td>3.32</td></tr>
<tr><td>50</td><td>3</td><td>57.22</td><td>3.54</td></tr>
<tr><td>75</td><td>4</td><td>55.16</td><td>3.37</td></tr>
</table>

Note: these results were based on 10W transmit power per sector. Scaling is applied to arrive at targeted EIRP values.

C.5 Massive MIMO simulations

The goal of the study is to evaluate the effects of mMIMO deployment on the level of interference measured at a reference point RP. The simulations account for the following assumptions:

1) A mMIMO antenna of 8x8x2 antenna elements is deployed as the gNB. Each of the 8x8 antenna element has 2 polarizations.
2) Cell load was used as a parameter with values 25%, 50% and 75%. From the value of the cell load the number of simultaneously active users in a snapshot[90] was derived using Poisson's distribution:

$$P(x > k) = \frac{\lambda^k\, e^{\lambda}}{k!}$$

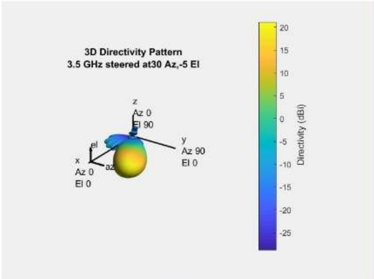
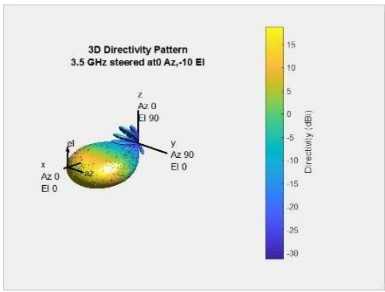
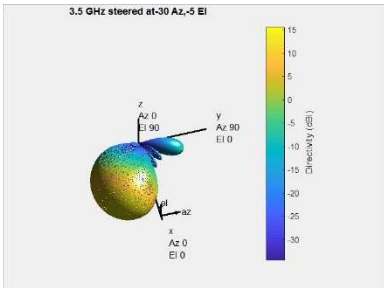
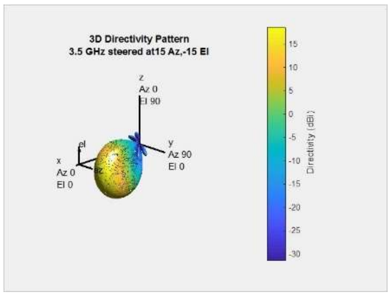
P(x>k) denotes probability of having number of users larger than k. Here k denotes number of occurrences (e.g. the number of active users at the observed snapshot), λ is an average number of occurrences per interval. Given the cell_load value, P (x>k) = cell_load denotes probability that k>0 users are simultaneously active. We can compute λ starting from the probability that no users are active i.e. P(x=0)= e^{λ} . Consequently 1-P = cell_load, i.e. 1-e^{λ} = cell_load . Here from λ is computed. Knowing λ we can calculate number of simultaneously active users in each snapshot. Note that 5G will use time division duplexing meaning that specific time intervals in which users are active will be used either for downlink (DL) or uplink transmission (UL). For example DL/UL transmission ration could be e.g. DL/UL=0.8/0.2 means that 80% of the traffic is oriented in the downlink.

3) Per each snapshot a random value k is generated based on Poisson's distribution with known λ. Antenna elements (AEs) of the 8x8x2 antenna array is divided among the active users. For example: a) in case of 1 user the complete array of 8x8x2 AEs is assigned to this user; b) in case of 2 simultaneously active users antenna array is split such that each user gets 8x8 AEs (each user using one polarization) c) for 3 user case each user

[90] Snapshots are time instants in which system performance is evaluated.

exploits a subarray of 8x4 AEs. Users sharing the same subarray are using different polarizations. d) In case of 4 simultaneously active user each user is assigned 8x4 AEs. Here, different antenna polarizations are also used. In our calculations we have limited the maximal number of active users to 4. This is done in order to avoid the creation of too wide antenna beams that could mutually interfere. The total transmit power is split equally among all active AEs. For example in case of 2 users each one acquires 100W. This 100W is further split over 8x8 AEs.

4) Three various sizes of antenna arrays were used i.e. 8x8, 8x4 and 4x8. Radiation patterns are created for these three (sub-)arrays for a limited set of elevation and azimuth angles to which the (sub-)array are pointing. In particular, there were 21 different directions i.e. combinations of (elevation, azimuth) for which antenna patterns were calculated.
   Note that even when pointing downwards e.g. elevation is -5°or even -15° a sub-array may still amplify signal in the boresight. Depending on the number of active users and size of antenna sub-arrays (e.g. 8x4 or 4x8) there is room for optimization in order to reduce inter-user interference as well as interference with respect to a selected reference point. At this stage of the simulations this optimization is not performed. Each AE (dipole) is modeled as a cosine element that results in low side-lobes and low distortion of the main beam. Antenna patterns for other dipole types are left for possible further study.

<table>
<tr>
<td>
8x8 array, elevation -5°, azimuth 30°</td>
<td>
8x4 array, elevation -10°, azimuth 0°</td>
</tr>
<tr>
<td>
4x4 array, elevation -5°, azimuth -30°,</td>
<td>
4x8 array, elevation -15°, azimuth 15°</td>
</tr>
</table>

5) In the simulations active users were randomly placed within -60° : 60° azimuth range i.e. within a sector of a gNB. Besides, the users were placed within the specified cell_range that is related to the inter-site distance (ISD) as cell_range=(2*ISD)/3. When the locations of all active user in a snapshot are defined each one of them is assigned an antenna sub-array with a beam that is pointing to the nearest location in the sector. This approximation (simplification) is performed due to the fact that the AE library covers 21 beam directions. The fact that we are using solely 21 beams per sub-array to cover the complete cell affects, to certain extent, the level of interference calculated at the reference point. This aspect can further be improved (if needed) by generating a larger library containing more antenna beams per larger number of directions (elevation, azimuth). This is a topic for possible further study.

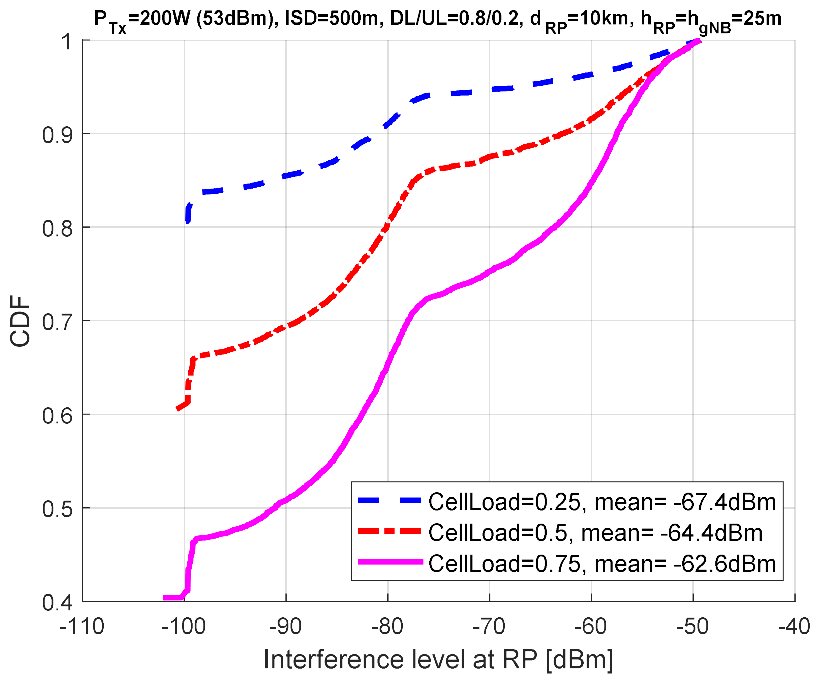
6) Figures below show empirical cumulative distribution function compute out of 100000 Monte-Carlo runs in which number of users and their locations were varied between the snapshots. In the simulations the following parameters/assumptions were used: 3 different cell_load assumptions, namely [0.25, 0.5, 075]. Height of the gNB (h_{gNB}) is equal to the height of the reference point (h_{RP}). Distance between the gNB and the RP is d_{RP}. The

RP is located at gNb's boresight. In the simulations solely one RP location is considered. Possible future research can derive statistics for a larger set of RPs. The level of interference at the RP is calculated by summing up signal power of different users calculated at the RP. The signal (interference) power sums up the transmit power assigned per sub-array, antenna gain of the corresponding sub-array and the free space path loss between the gNB and RP. ISD defines inter-site distance i.e. the distance between the gNBs. DL/UL parameter specifies the ratio between downlink (DL) and uplink (UL) traffic in snapshots were there are active users.

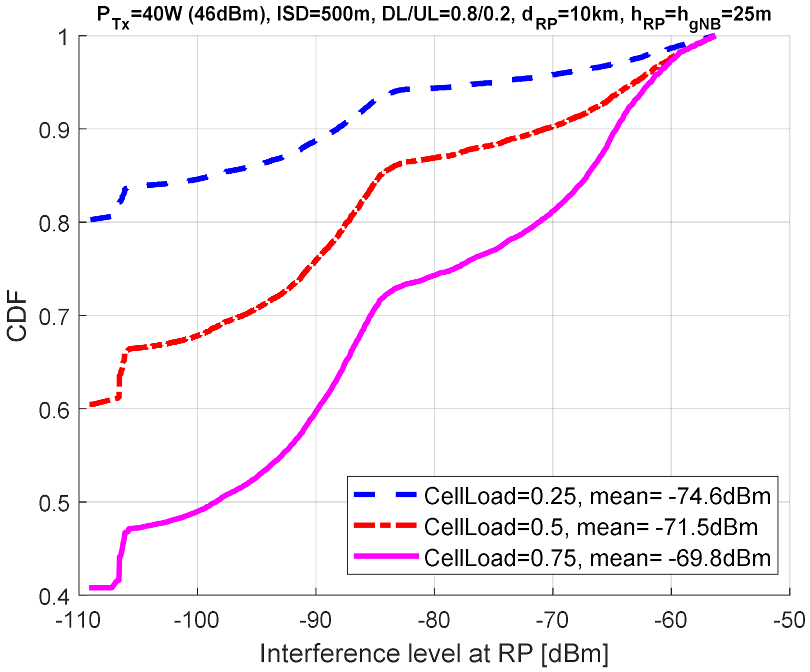
7) Path loss calculations assume free space path loss at frequency f_c=3.5GHz.

Simulations

1) **Deployment scenario Ma_1, AE:8x8x2, ISD = 500m, P_{Tx} = 200W (53dBm), d_{RP}=10km (single RP in the gNB boresight), DL/UL=0.8/0.2, h_{RP}=h_{gNB}=25m , f_c=3.5GHz**



2) Deployment scenario Ma_1, AE:8x8x2, ISD = 500m, P_{Tx} = 40W (46dBm), d_{RP}=10km (single RP in the gNB boresight), DL/UL=0.8/0.2, h_{RP}=h_{gNB}=25m, f_c=3.5GHz



Ma_1	Mean Interference Level (I) at Reference Point [dBm]		
CellLoad	Active Antenna System (AAS), Ptx=46dBm	Conventional 'Kathrein' Sector Antenna (CSA), Ptx=46dBm, Downtilt=4°	$\Delta = I_{CSA} - I_{AAS}$ [dB]
0.25	-74.6	-66.6	8
0.5	-71.5	-66.6	4.9
0.75	-69.8	-66.6	3.2

The table shows mean interference level [dBm] calculated at the reference point for the case when gNB is implemented as a) Active Antenna System (8x8x2) and b) conventional 'Kathrein' sector antenna with the indicted downtilt. For the case of the CSA interference level is calculated using the following formula:

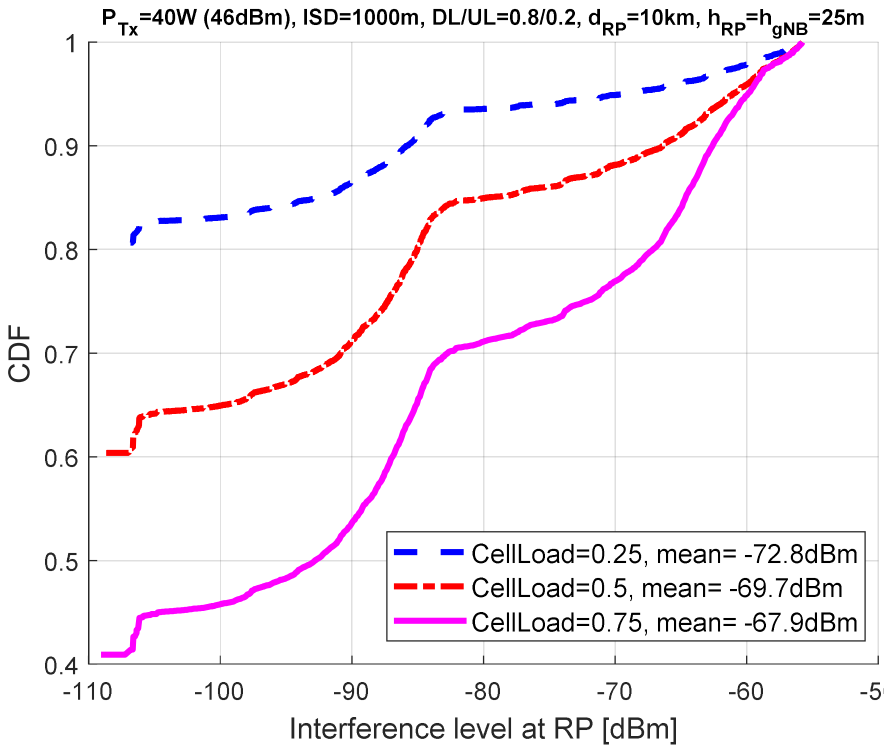
$$\text{InterferenceLevel} = P_{tx} + g_{dBi} - Att_{Atzerodeg} - FSPL;$$

Where,
Ptx is the gNB transmit power [dBm],
g_{dBi} is antenna gain [dBi],
$Att_{Atzerodeg}$ is attenuation of the gNB antenna in the direction of the reference point [dB],

FSPL represents the free space path loss for the reference point located at 10km and calculated at 3.5GHz carrier frequency.

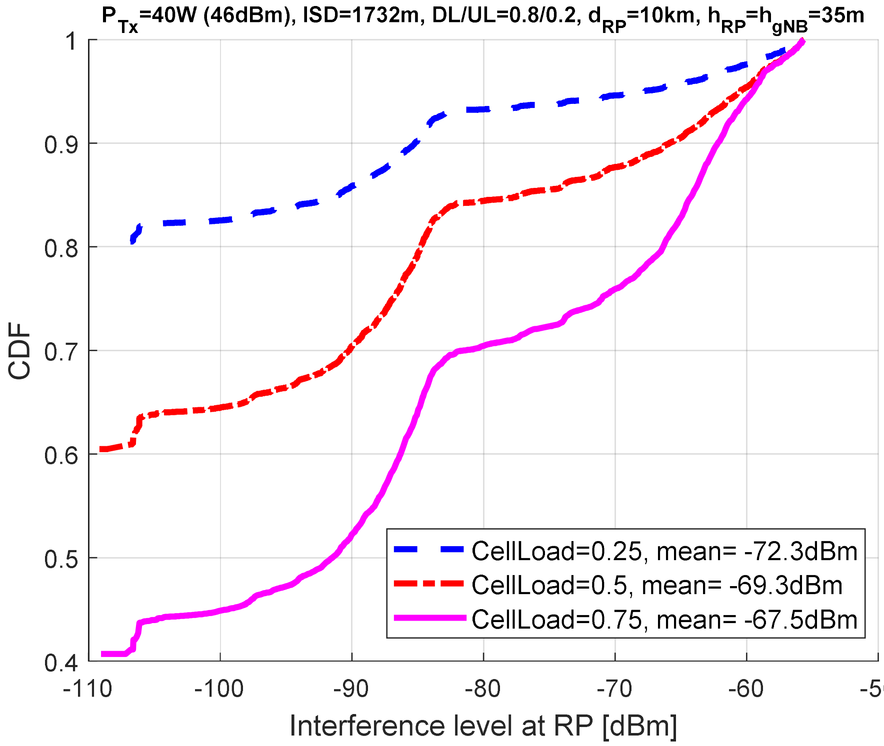
The value of Δ indicates the difference between the interference level created by the conventional sector antenna and interference level emerging in the case active antenna system is deployed. Δ is expressed in [dB].

3) Deployment scenario Ma_2, AE:8x8x2, ISD = 1000m, P_{Tx} = 40W (46dBm), d_{RP}=10km (single RP in the gNB boresight), DL/UL=0.8/0.2, h_{RP}=h_{gNB}=25m, f_c=3.5GHz



Ma_2	**Mean Interference Level at Reference Point [dBm]**		
CellLoad	**Active Antenna System (AAS), Ptx=46dBm**	**Conventional 'Kathrein' Sector Antenna (CSA), Ptx=46dBm, Downtilt=2°**	**Δ=I_{CSA}-I_{AAS} [dB]**
0.25	**-72.8**	**-61.6**	**11.2**
0.5	**-69.7**	**-61.6**	**8.1**
0.75	**-67.9**	**-61.6**	**6.3**

Deployment scenario Ma_3, AE:8x8x2, ISD = 1732m, P_{Tx} = 40W (46dBm), d_{RP}=10km (single RP in the gNB boresight), DL/UL=0.8/0.2, h_{gNB}= h_{RP}=35m, f_c=3.5GHz

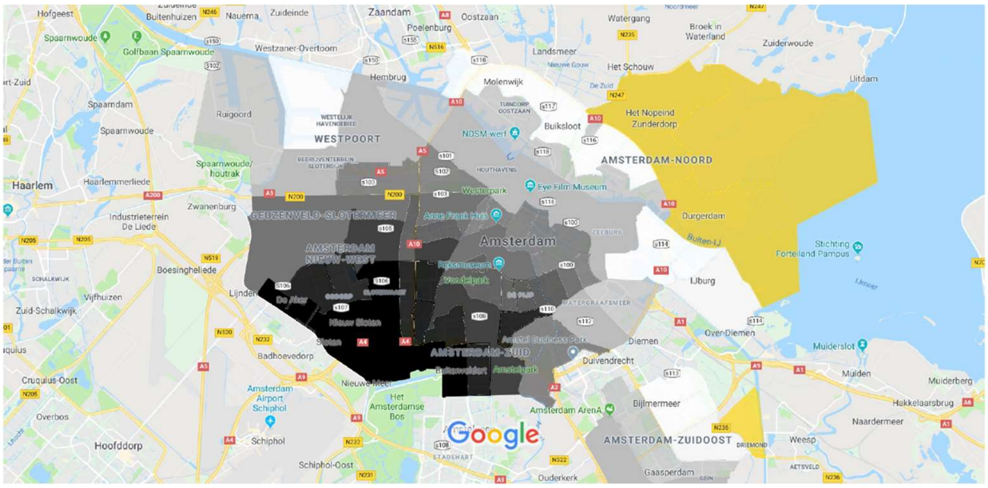


Ma_3	**Mean Interference Level at Reference Point [dBm]**		
CellLoad	**Active Antenna System (AAS), Ptx=46dBm**	**Conventional 'Kathrein' Sector Antenna (CSA), Ptx=46dBm, Downtilt=2°**	**$\Delta=I_{CSA}-I_{AAS}$ [dB]**
0.25	**-72.3**	**-61.6**	**10.7**
0.5	**-69.3**	**-61.6**	**7.7**
0.75	**-67.5**	**-61.6**	**5.9**

C.6 Dominant edge effect

The suspected effect in urban areas was that emissions which escape from these areas are predominantly generated by base stations relative close towards the urban edge (where urban changes to rural). In other words, emissions originating from deep urban areas would almost disappear. Ignoring this effect may lead to an overestimation of the EEIRP value of an entire city like Amsterdam.

We did some investigations into this suspected effect using the propagation tool, but we could not easily obtain clear proof of this phenomenon. The experiment was conducted on Amsterdam. The hypothesis was to apply EEIRP correction factors to PC-4 areas which lay deeper in Amsterdam, at least from the perspective of Burum. To this end, the PC-4 areas were ranked as displayed below.



We set up a deployment in PC-4 area 1017 and then determined the signal strength values at observation points at sufficiently far distance of this areas. Each time an additional PC-area was inserted (1017+1072; 1017+1072+1078; 1017+1072+1078+1083) and the experiment was repeated. We did the experiment for different antenna heights. The results are listed below.

Area Type	PC4	Tx height (m)	PC 1017 μ (dBm)	PC 1017 σ (dB)	PC 1017+1072 μ (dBm)	PC 1017+1072 σ (dB)	PC 1017+1072+1078 μ (dBm)	PC 1017+1072+1078 σ (dB)	PC 1017+1072+1078+1083 μ (dBm)	PC 1017+1072+1078+1083 σ (dB)
1	1017 (Amsterdam)	6	20.18	0.66	17.55	0.51	16.38	0.71	15.80	0.86
		12	28.65	0.47	23.54	1.09	19.98	0.04	19.28	0.24
		25	36.06	0.13	33.80	0.05	33.79	0.08	31.48	1.30

The results indicated that the suspected dominant edge effect was quite weak. We repeated the experiment for Groningen. Those results are shown below which did not provide convincing evidence either.

Area Type	PC4	Tx height (m)	PC 9712 μ (dBm)	PC 9712 σ (dB)	PC 9712+9717 μ (dBm)	PC 9712+9717 σ (dB)	PC 9712+9717+9742 μ (dBm)	PC 9712+9717+9742 σ (dB)	PC 9712+9717+9742+9743 μ (dBm)	PC 9712+9717+9742+9743 σ (dB)
1	9712 (Groningen)	6	17.54	0.4	19.72	0.04	18.41	0.13	18.36	0.52
		12	27.96	0.14	35.04	0.1	27.64	0.46	26.44	0.31
		25	35.71	0.25	34.71	0.24	33.83	1.17	28.31	3.08

It was therefore decided to ignore this effect in our impact assessment. This may have led to a slight overestimation of emissions escaping from large cities.

C.7 5G deployment scenarios specification

A detailed and complementary specification of the 5G scenarios from our framework is listed below[91].

Baseline (2018):

Snapshot		T=T0 (2018)	BASELINE		
		Type I	Type II	Type III	Type IV
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
Baseline BH Traffic Load (%)		50%	50%	35%	20%

Scen S1:

Snapshot	2020				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot since T0		3%	3%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		65%	72%	60%	53%
Average Traffic Load at snapshot		5%	5%	4%	2%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwidth (GHz)	0,10				

Scen S2:

Snapshot	2020				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot		3%	3%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		65%	72%	60%	53%
Average Traffic Load at snapshot (%)		5%	5%	4%	2%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	0,1				

Scen S3:

Snapshot	2020				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot		3%	3%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		65%	72%	60%	53%
Average Traffic Load at snapshot		5%	5%	4%	2%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	0,1				

[91] All figures listed here regarding growth in infrastructure and utilisation across the four 4 geotypes are TNO-estimates, combined with averaged data retrieved from the Antenna Register. The technology efficiency figures for urban and rural are taken from an existing 3GPP source. The figure for suburban is obtained through simple interpolation.

Scen S1a:

Snapshot	2020				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot since T0		3%	3%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot		5%	5%	4%	2%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwidth (GHz)	0,10				

Scen S2a:

Snapshot	2020				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot		3%	3%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot (%)		5%	5%	4%	2%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	0,1				

Scen S3a:

Snapshot	2020				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot		3%	3%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot		5%	5%	4%	2%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	0,1				

Scen S1b:

Snapshot	2020				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot since T0		6%	6%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot		5%	5%	4%	2%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwidth (GHz)	0,10				

Scen S1c:

Snapshot	2024				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot since T0		3%	3%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot		50%	50%	35%	20%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwidth (GHz)	0,10				

Scen S2c:

Snapshot	2024				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot		3%	3%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot (%)		50%	50%	35%	20%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	0,1				

Scen S3c:

Snapshot	2024				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot		3%	3%	3%	3%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot		50%	50%	35%	20%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	0,1				

Scen S1d:

Snapshot	2024				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot since T0		7,2%	7,2%	7,2%	7,2%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot		50%	50%	35%	20%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwidth (GHz)	0,10				

Scen S2d:

Snapshot	2024				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot		7%	7%	7%	7%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot (%)		50%	50%	35%	20%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	0,1				

Scen S3d:

Snapshot	2024				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot		7%	7%	7%	7%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot		50%	50%	35%	20%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	0,1				

Scen S1e:

Snapshot	2028				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot since T0		11,6%	11,6%	15,0%	20,0%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot		50%	50%	40%	40%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwidth (GHz)	0,10				

Scen S2e:

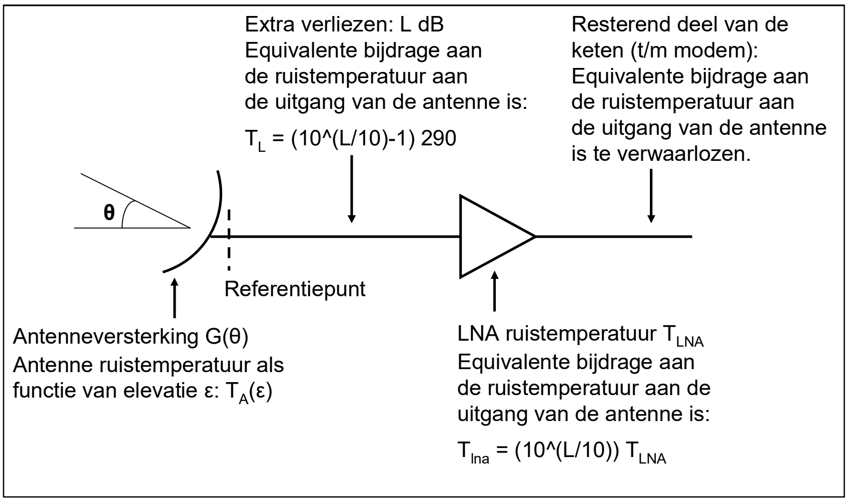
Snapshot	2028				
		Type I	Type II	Type III	Type IV
MACRO growth (%) at snapshot		12%	12%	15%	20%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot (%)		50%	50%	40%	40%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	0,1				

Scen S3e:

Snapshot	2028				
		Type I	**Type II**	**Type III**	**Type IV**
MACRO growth (%) at snapshot		12%	12%	15%	20%
Baseline MACRO 5G utilisation (%)		65%	72%	60%	53%
MACRO 5G utilisation (%) at snapshot		100%	100%	100%	100%
Average Traffic Load at snapshot		50%	50%	40%	40%
Average Spectrum Efficiency 5G-NR (bit/s/Hz)		7,80	7,80	5,00	3,30
NR Bandwith (GHz)	**0,1**				

C.8 Burum receiver model

C.8.1 Receiver model



C.8.2 Measurements

For a number of satellites, the signal strength (C) of various carriers have been measured recently for a period of time[57]. Combined with noise (N) measurements, this allowed the C/N distribution of the signals to be determined. All signals received with a carrier-to-noise less than a certain minimum value $(C/N)_{min}$ are considered to be lost, since their content cannot be reliably retrieved.

C.8.3 Production Loss (calculation)

All signals with carrier-to-noise (C/N) equal or exceeding $(C/N)_{min}$ have been divided in intervals; with each interval i containing the number of signals n_i having a carrier-to-noise within the range $(C/N)_{min}$ + 0.1 x i - 0.05 dB and $(C/N)_{min}$ + 0.1 x i + 0.05 dB. Signals in interval i are received with a C/N which is 0.1 x i dB above $(C/N)_{min}$. When the received interference level (I), considered as white noise, increases the noise level by 0.1 x i dB or more, the content of the signals in interval i can no longer be retrieved. Given the EIRP of the interfering transmitter and the received interference level, the corresponding time percentage p_i of this happening is obtained from the ITU-R P.452 propagation model. In each intervals i the number of signals n_i times p_i is then the number of signals of which the content can no longer be retrieved and have to be considered lost. Summing over all intervals and dividing by the total number of signals in all intervals then results in the total percentage of signals of which the content can no longer be retrieved due to interference. This is called the production loss.

All numeric values and measurement results mentioned above are confidential. They are contained in a separate Confidential report[92].

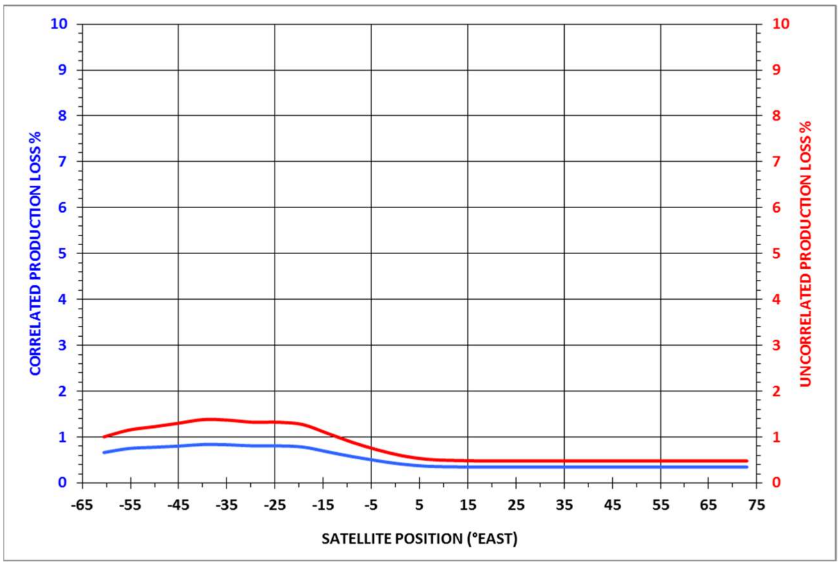
[92] J. van den Oever, H.J. Dekker, Metingen SGS Burum, TNO Report TNO 2018 R11146, October 2018

D Results Impact Assessment

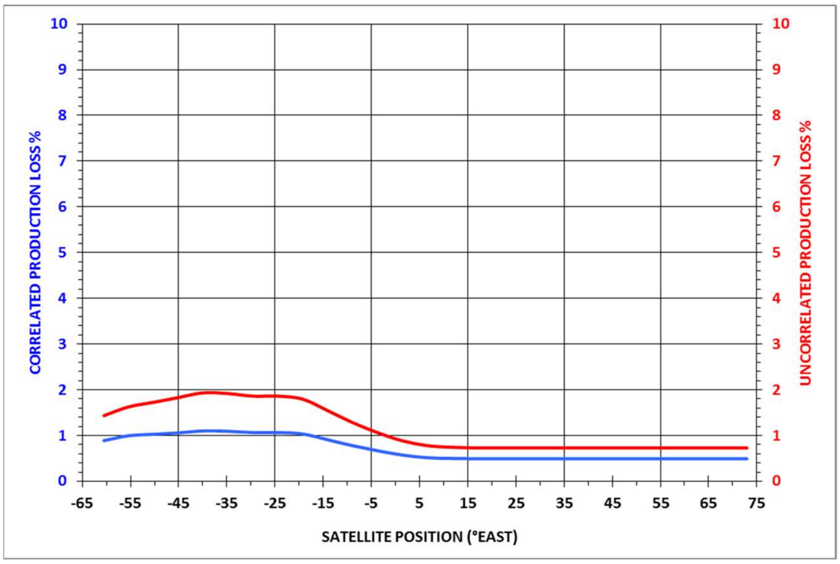
D.1 Burum production loss results (conventional antennas in 5G, 20 km exclusion)

D.1.1 Scenario 1 (4 main cities)

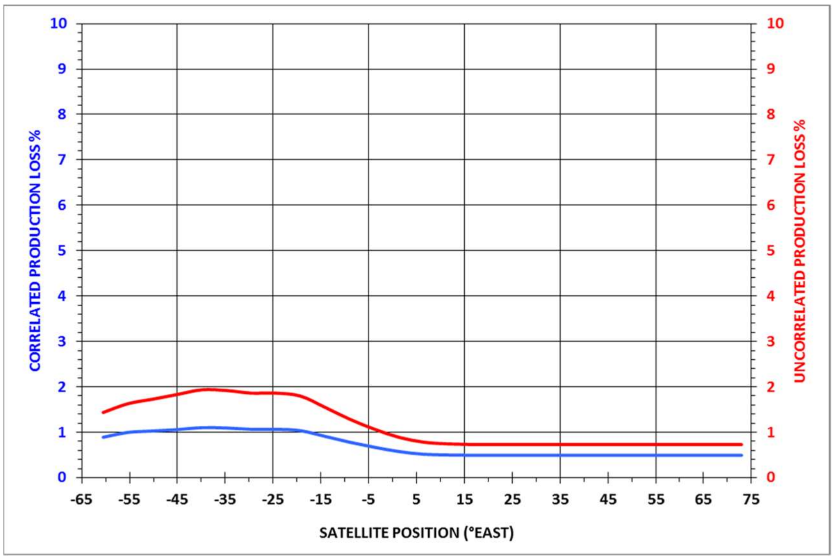
Scenario 4 main cities
Snapshot: Early adoption
Strategy: Sparse coverage



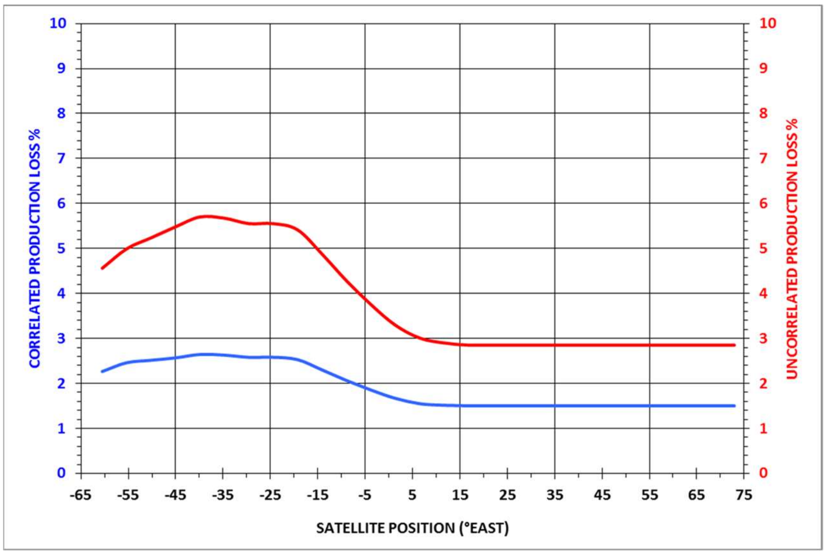
Scenario: 4 main cities
Snapshot: Early adoption
Strategy: Robust coverage



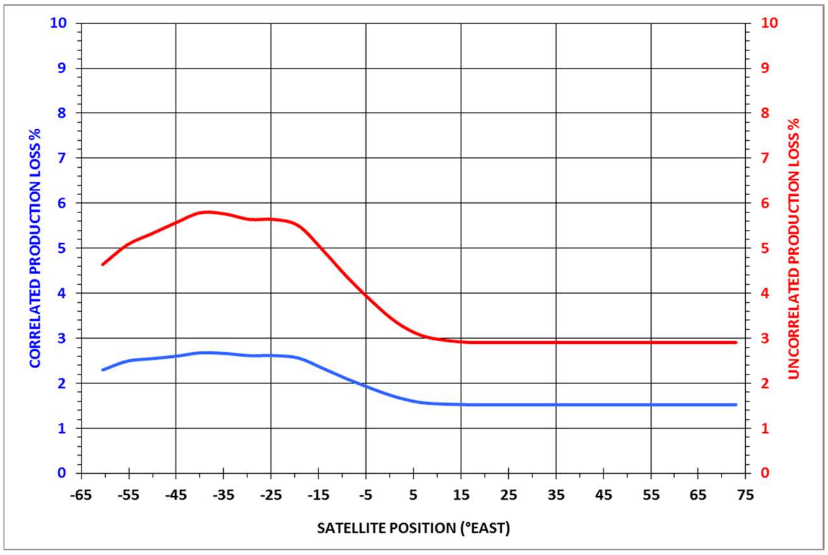
Scenario: 4 main cities
Snapshot: Early adoption
Strategy: Capacity



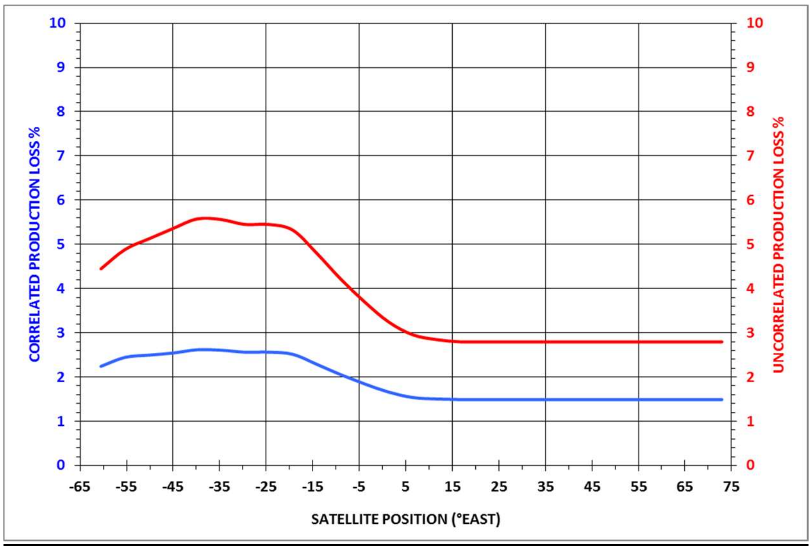
Scenario: 4 main cities
Snapshot: Mature adoption
Strategy: Robust coverage



Scenario: 4 main cities
Snapshot: Mature adoption
Strategy: Capacity

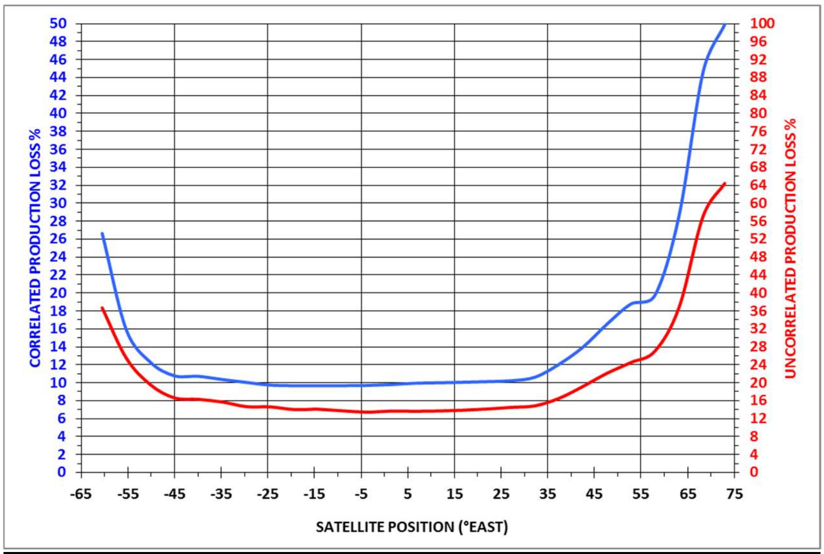


Scenario:	4 main cities
Snapshot:	Future Evolution
Strategy:	Capacity

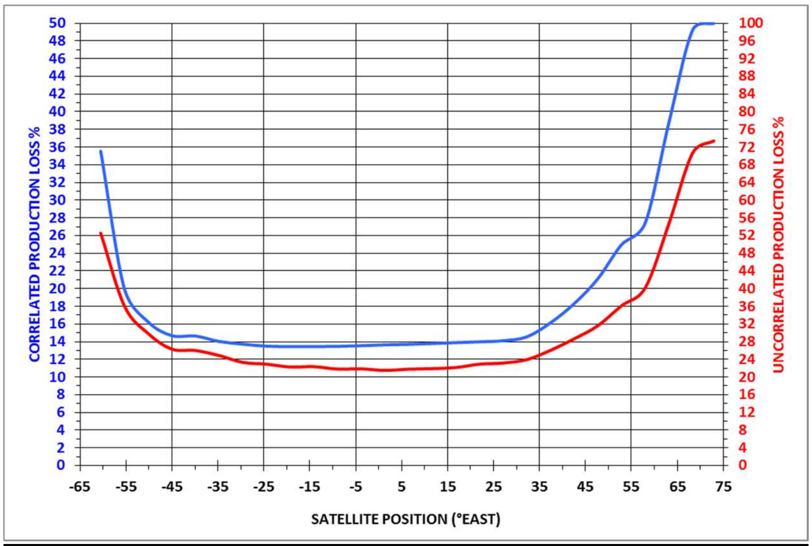


D.1.2 *Scenario 2 (Urbanized areas in NL)*

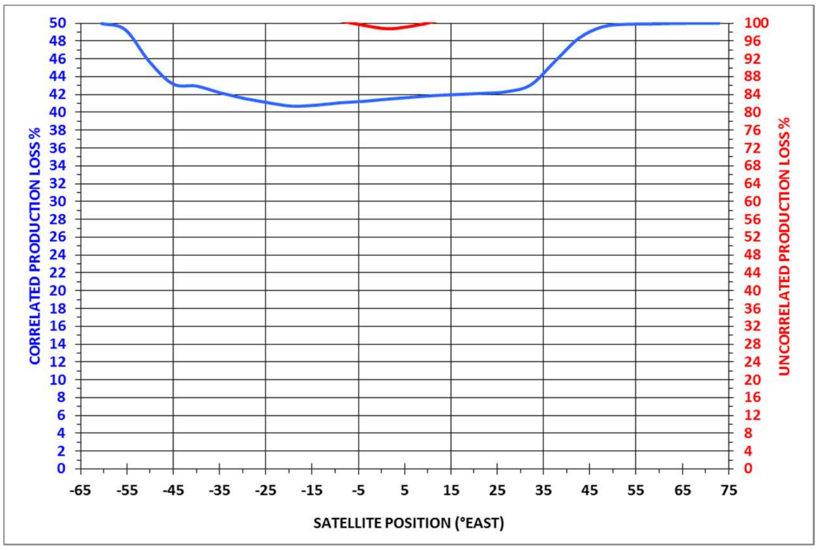
Scenario	NL-Urbanized
Snapshot:	Early adoption
Strategy:	Sparse coverage



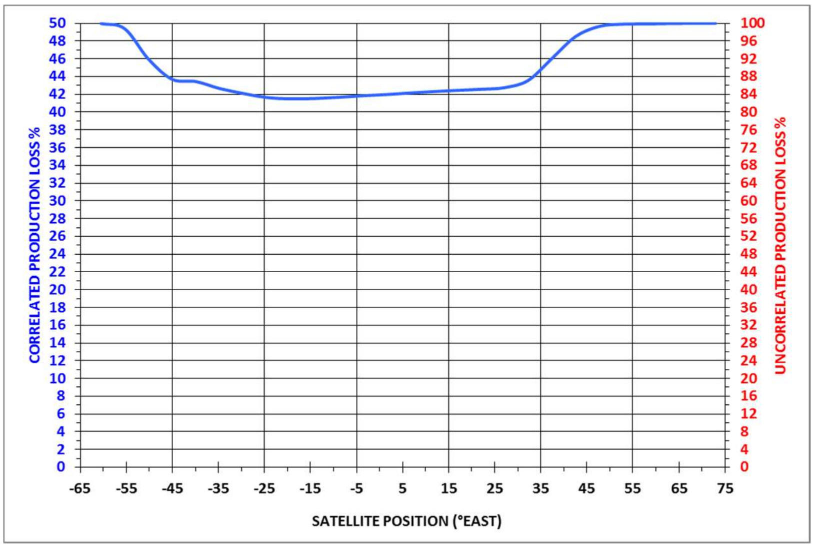
Scenario: NL-Urbanized
Snapshot: Early adoption
Strategy: Robust coverage



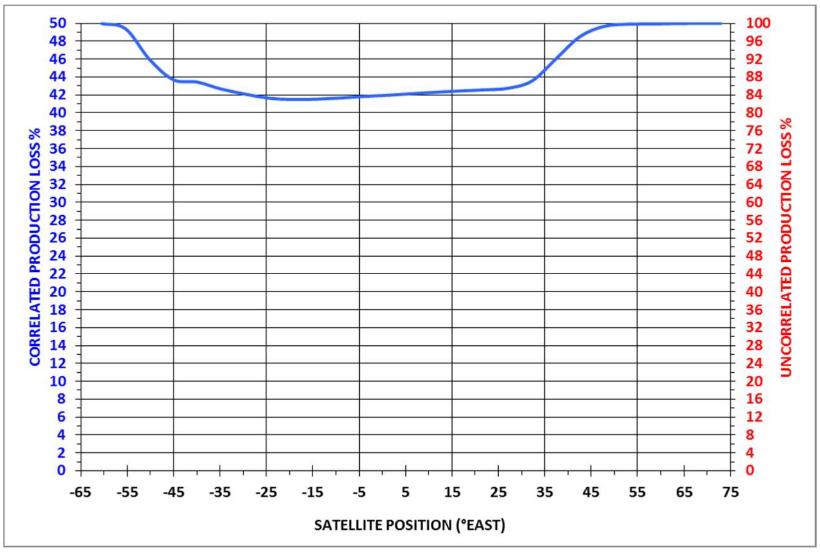
Scenario: NL-Urbanized
Snapshot: Early adoption
Strategy: Capacity



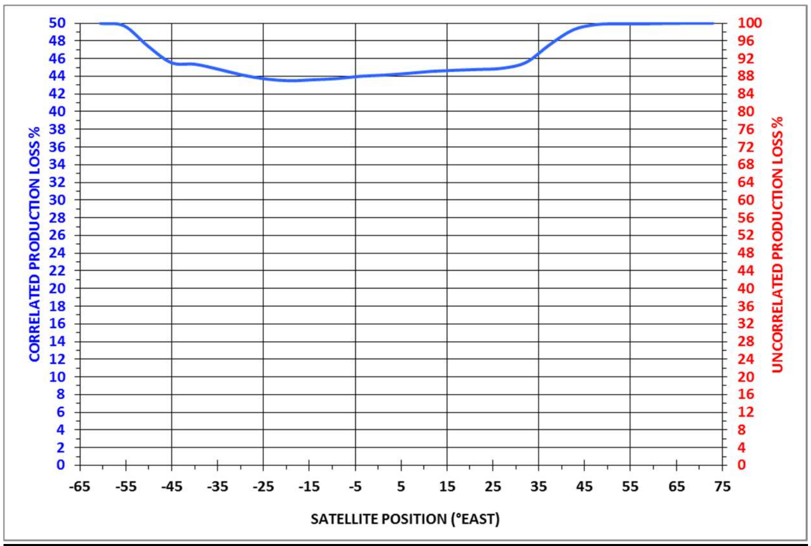
Scenario:	NL-Urbanized
Snapshot:	Mature adoption
Strategy:	Robust coverage



Scenario:	NL-Urbanized
Snapshot:	Mature adoption
Strategy:	Capacity

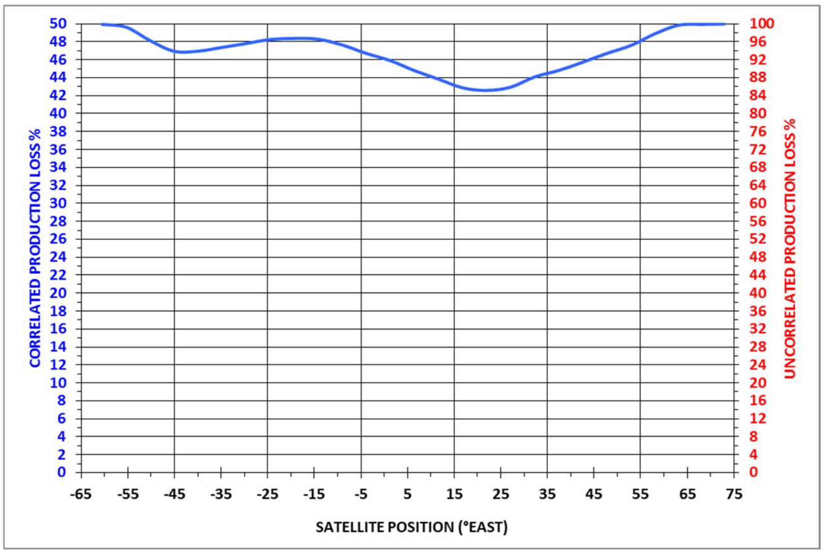


Scenario: NL-Urbanized
Snapshot: Future Evolution
Strategy: Capacity



D.1.3 *Scenario 3 (Whole country)*

Scenario NL
Snapshot: Early adoption
Strategy: Sparse coverage



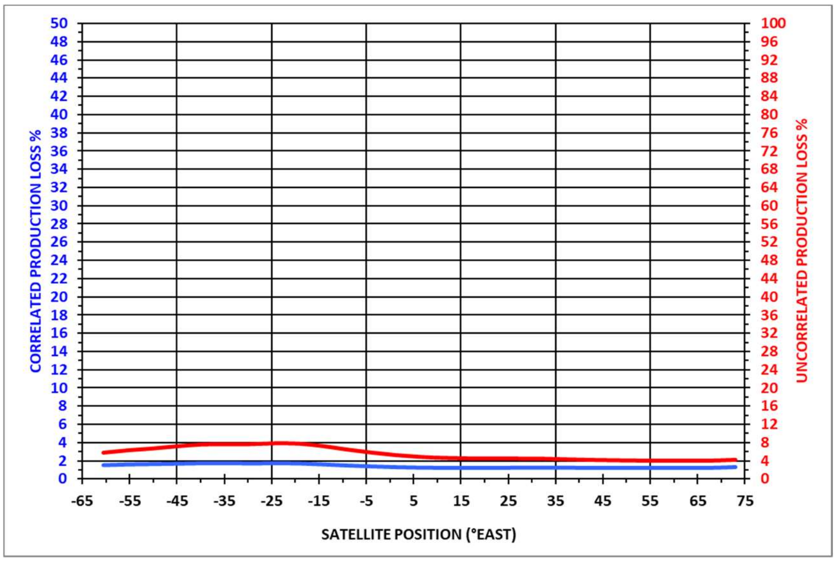
Remaining scenarios all generate production loss figures of 50%/100%. These are not included here.

D.2 Burum production loss results (Adaptive antennas in 5G)

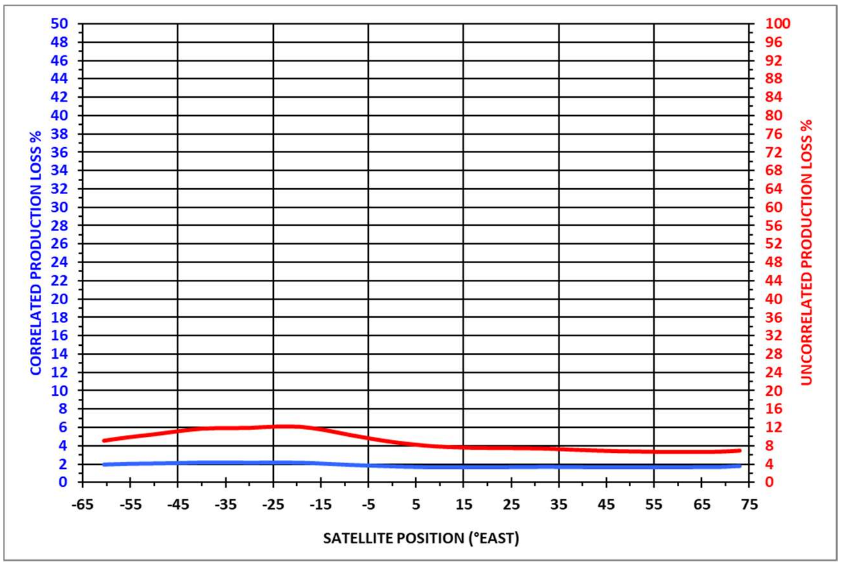
The results shown below are based on the use of adaptive antenna systems throughout the network. The result is only shown for scenarios 2 and 3. **In all cases a 50 km exclusion zone is maintained!**

D.2.1 Scenario 2 (Urbanized areas in NL)

Scenario:	NL-Urbanized
Snapshot:	Mature adoption
Strategy:	Capacity

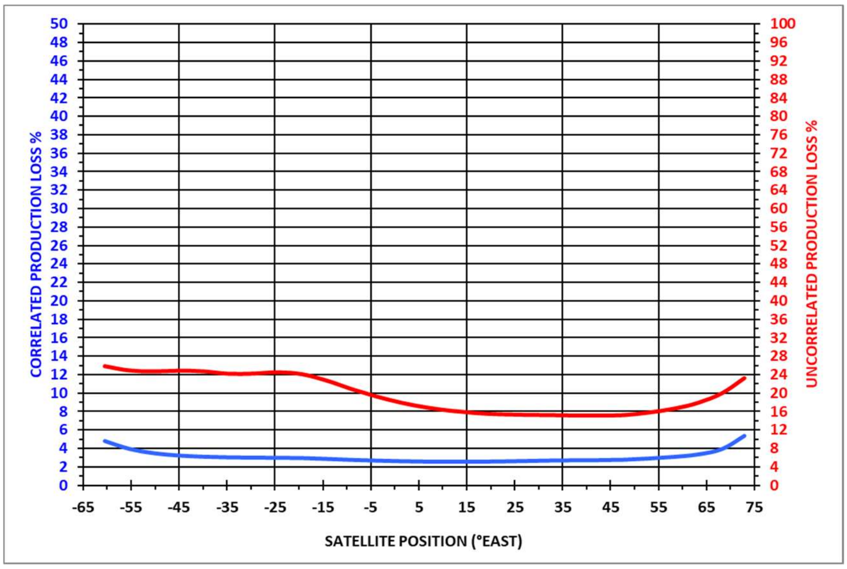


Scenario: NL-Urbanized
Snapshot: Future Evolution
Strategy: Capacity

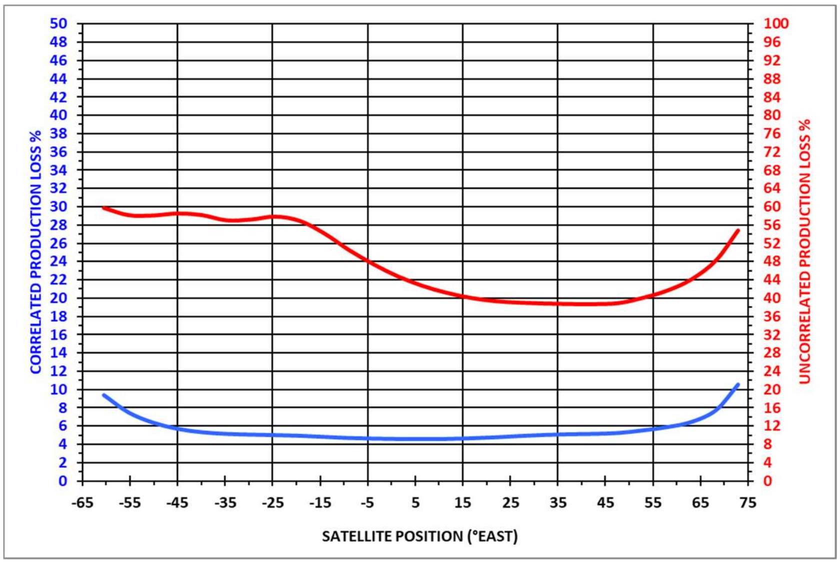


D.2.2 *Scenario 3 (whole country)*

Scenario: Whole country
Snapshot: Mature adoption
Strategy: Capacity



Scenario:	Whole country
Snapshot:	Future Evolution
Strategy:	Capacity



E Licensed Shared Access

E.1 Introduction to Licensed Shared Access

According to the RSPG of the EC[93] the definition/description of LSA is:

> *"Licensed Shared Access (LSA) could provide new sharing opportunities on a European scale under a licensing regime, while safeguarding national current spectrum usages which cannot be refarmed. It is not intended that LSA will be an initial or temporary phase prior to the refarming of any band. Consequently, general sharing conditions should be agreed at European level, taking into account national particularities in bands designated for LSA at EU level, thus offering new opportunities for providing services with a good Quality of Service in spectrum within Europe. This new concept needs to be further developed, in particular regarding the possibility to dynamically modify licensing conditions within the framework of the recently adopted EU regulation".*

Reading this definition there are several relevant aspects to LSA:
- LSA is a spectrum management tool under a spectrum licensing regime;
- It aims at enabling the introduction of new users in a frequency band additional to the incumbent services;
- The new users, LSA licensees, get access to the spectrum subject to conditions (regulatory constrains) contained in the license;
- Incumbent users and LSA licensees operate different radio services under different regulatory conditions;
- The objective of LSA is to ensure guarantees to incumbent users as well as LSA licensees in terms of spectrum access and protection against harmful interference;
- As such LSA will in principle allow both the incumbent users as well as the LSA licensees to obtain a predictable quality of service.

The last-mentioned aspect is an important requirement for LSA: a clear objective is to provide a good QoS level also for LSA users.

ECC Report 205 on Licensed Shared Access[94] describes the scope and implementation of LSA in more detail. Here the observation is made that sharing through LSA requires close cooperation between the incumbent and the LSA licensee, due to the priority in the spectrum access right. The conclusion is that LSA should be implemented on a voluntary basis. In fact, LSA can only work if there is a realistic basis to share spectrum with a clear and commonly agreed framework of conditions. This framework is to be developed in cooperation between the incumbent user(s), the prospective LSA licensee(s) and the national telecommunications regulatory authority (NRA). The NRA will also have the responsibility to grant the licenses to the LSA licensees and keep control on the observance of the license conditions.

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[93] Source: EUROPEAN COMMISSION, Radio Spectrum Policy Group, *RSPG opinion on Licensed Shared Access*, RSPG13-538, Brussels, 12 November 2013

[94] Source: ECC Report 205, *Licensed Shared Access (LSA)*, February 2014

E.2 LSA in the 2300 – 2400 MHz band (IMT TDD Band 40)

Bandwidth expansion for mobile network operator

The ETSI technical report TR 103 113, describes the framework for 'Mobile broadband services in the 2 300 MHz - 2 400 MHz frequency band under Licensed Shared Access regime'[95]. In this report the remark is made that spectrum sharing under the LSA framework is binary by nature, as it permits spectrum use by either the incumbent or the LSA licensee.

For this purpose, three different LSA scenarios are considered:

1) Incumbent and LSA licensee share the same spectrum in the same location on a time basis;
2) Incumbent and LSA licensee use the same spectrum at the same time in different locations;
3) LSA licensee uses in the same location and time a portion of the band not being utilized by the incumbent

The practical LSA implementation for this case is sketched as follows:

- A mobile network operator operating LTE in a licensed band in a region applies for an individual authorization to use radio frequencies within the 2 300 - 2 400 MHz frequency band in that same region to use a portion of this band under the LSA regime for LTE.
- The conditions to use the spectrum (determined by the NRA) can be made available in an information repository that can be accessed by the mobile network operator's Operation, Administration and Maintenance system (OAM).
- The mobile network operator also operates LTE in a licensed band in the region and provisions the same or additional base stations to support the authorized portion of the 2 300 - 2 400 MHz band.
- At the appropriate time indicated by the information repository, the mobile network operator's OAM system instructs the relevant base stations to enable transmission in the allowed portion of the 2 300 - 2 400 MHz band.
- When the granted time period for the operation in the authorized portion of the 2 300 - 2 400 MHz band expires, the mobile network operator's OAM system instructs the relevant base stations to disable transmission in the allowed portion of the 2 300 - 2 400 MHz band.

System architecture and high-level procedures for operation of Licensed Shared Access (LSA) in the 2 300 MHz - 2 400 MHz band are in Figure E.1[96]

---

[95] Source: ETSI TR 103 113 V1.1.1 (2013-07), Technical Report, *Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference document (SRdoc); Mobile broadband services in the 2 300 MHz - 2 400 MHz frequency band under Licensed Shared Access regime*

[96] Source: ETSI TS 103 235 V1.1.1 (2015-10), TECHNICAL SPECIFICATION, Reconfigurable Radio Systems (RRS); *System architecture and high level procedures for operation of Licensed Shared Access (LSA) in the 2 300 MHz - 2 400 MHz band*

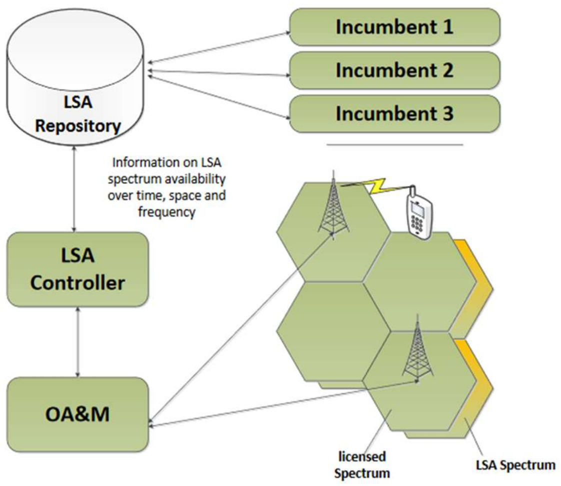

Figure E.1 LSA Architecture. Source: Intel[97].

A pilot based on this LSA approach is described in a whitepaper[98]. In the Netherlands an LSA concept for Program Making Special Events (PMSE) is being piloted. It is basically an on-line booking system for cordless cameras, portable video links and mobile video links, which may also be airborne. The conditions for the use of the spectrum are contained in a condense document[99]

E.3 LSA in the 3550 – 3700 MHz (USA)

In April 2015, the Federal Communications Commission (FCC) in the United States[100] formally established a regulatory framework for Citizen Broadband Radio Service (CBRS) to share the 3.5 GHz band (3550-3700 MHz) with the incumbent services: military radars and fixed satellite stations. With this regulatory framework additional spectrum is made available commercial wireless broadband in a flexible manner, while providing interference protection for the incumbent users. The framework consists of a 3-tier approach for the coordination of spectrum access between the incumbent users (military radars and satellite ground stations) and the new entrants (commercial wireless broadband network operators). The 3 tiers are:

- Tier 1: Incumbent use – military radars and fixed satellite stations;
- Tier 2: Priority Access License (PAL);
- Tier 3: General Authorized Access (GAA).

The access to spectrum in this 3-tier approach is shown in Figure E.2.

The Spectrum Access System that is established for the CBRS band is based on the following principles:

---

[97] Source: Intel, *Spectrum Sharing: Licensed Shared Access (LSA) and Spectrum Access System (SAS)*, White paper, October 2015

[98] Source: Ericsson, Qualcomm, RED, La French Tech, *World's first Licensed Shared Access with Carrier Aggregation pilot January 2016 – June 2016, Paris, France*

[99] Source: Agentschap Telecom, *Spelregels pilot LSA boekingssysteem*, vers. 1.2 (2017)

[100] Source: Federal Communications Commission (FCC), *Report and order and second further notice of proposed rulemaking, In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*, FCC 15-47, 21 April 2015

- Tier 1 systems are protected from possible interference by lower tier users (PAL and GAA);
- Tier 2 PAL users have next highest priority and are protected from possible interference by Tier 3 (GAA) users.

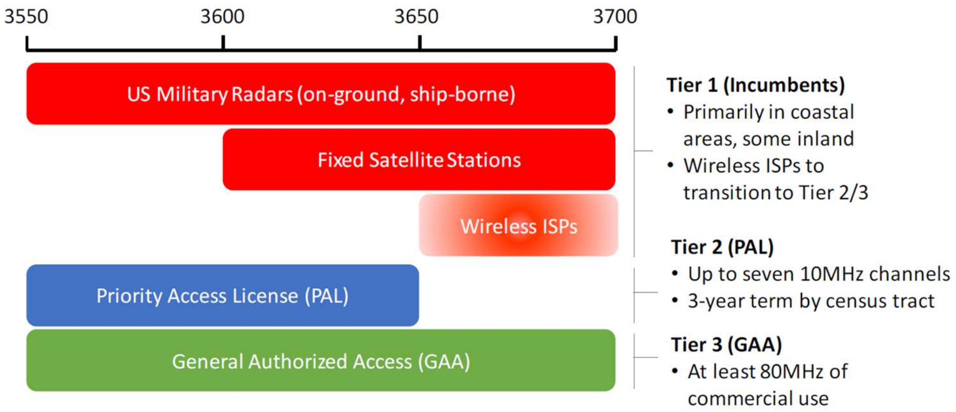

Figure E.2: 3-Tier Shared Spectrum Licensing Structure[101]

For Tier 2, in the CBRS spectrum access system it has been chosen to make available 7 PAL licenses of 10 MHz each for a certain limited area for a period of 3 years. The Tier 2 licensee should have the notice that the PAL frequency range may vary over time, as the incumbent use may change over time.

Tier 3 GAA users are permitted to use portions of the 3550 – 3700 MHz band that are not assigned to higher tier users. GAA operation does not require a license, but GAA operators must coordinate their use of the spectrum through the dynamic spectrum sharing system, depicted in Figure E.3.

[101] Source: CBRS white paper, Mobile Experts, *CBRS: New Shared Spectrum Enables Flexible Indoor and Outdoor Mobile Solutions and New Business Models*, March 2017

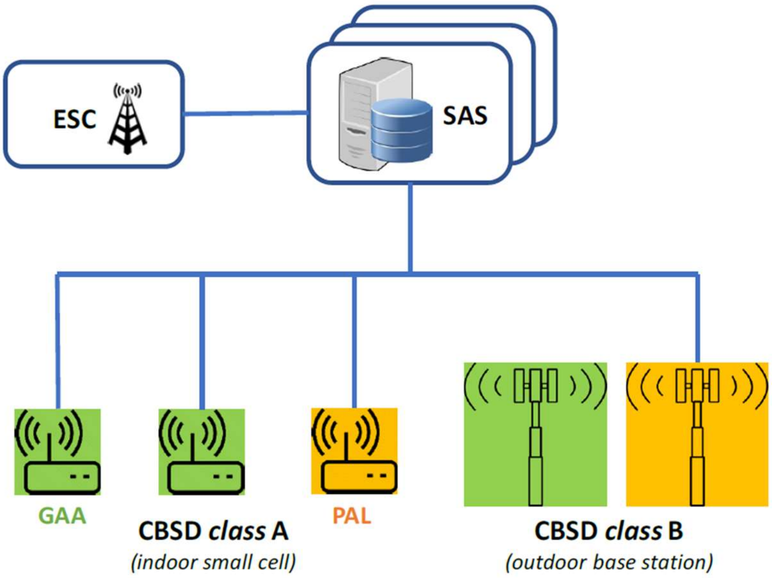

Figure E.3: Schematic overview of the Spectrum Access System. Source: CBRS White paper

The Spectrum Access System (SAS) maintains a database with information of all CBRS base stations, including their Tier status, geographical location. Multiple sensor called Environmental Sensing Capability (ESC) are used to sense the spectrum. ESCs are deployed in regions where Tier 1 applications are expected (in this specific case of military radars and satellite station in the US, mostly in coastal areas). When signals of incumbent users are detected, the ESC alerts the SAS, which then directs the CBRS bases stations in that area to move to other channels.

As such the SAS is an implementation of the 3-tier spectrum sharing mechanism established by the FCC ruling. This is done via centralized, dynamic coordination of spectrum channel assignments across all CBRS base stations in a region. Aspects of this approach may be considered in the case of sharing between 5G and satellite interception in the Netherlands.

F Alternative interception based on phased array principles

F.1 Introduction

In this section the potential benefits and caveats of employing a multi-antenna concept are explored. In this approach the total combined response from all antenna elements can be used to model the entire antenna array as a single antenna. By adding element specific weights in the summation of these signals a highly directive antenna pattern can be obtained, which can be designed to provide a maximum gain for signals incident from one direction and/or maximum attenuation from signal from other directions.

This concept is referred to as *beamforming*, or *spatial filtering*. Here the latter provides a more intuitive naming convention for the problem at hand, where the total signal received by the antenna array is comprised of the intended signal to be received ('the desired signal'), one or more interfering signal sources and noise. In general the desired and interfering sources are incident on the antenna array from different directions, making the possibility to apply filtering based on the direction of incidence an attractive potential solution.

Furthermore, by dynamically changing the weighting factors of each element the directivity of the antenna array can be steered (to some extend), a concept commonly referred to as *beam steering*. Also, multiple weighted summations can be applied in parallel (with different weighting factor) which allows the antenna array to apply spatial filtering with respect to multiple desired signal simultaneously.
The extent to which an array of antennas is able to provide sufficient spatial filtering in order to provide the gain and/or attenuation necessary to meet the signal-to-interference-noise-ratio (SINR) required for proper signal reception depends on a number of factors such as

- The distance of the receiving antenna elements (relative to each other);
- The weighting factors applied to the received signals;
- The number of receiving antenna elements;
- The type(s) of receiving antennas;
- The dimensions of the array system (related to the number of elements and inter-element distance).

A more detailed overview of how these factors determine the total response of the antenna array is provided later in this Annex. In the field of array pattern synthesis a number of methods exist, but even from this list of factor it can already be seen that solving such an optimization problem can become quite complex, involving many variables.
The number of variables in het antenna array model can be reduced through a number of assumptions which are valid under the assumption of far-field conditions and assuming that the radiation pattern of each individual element is the same. Further reduction of the number of variables follows from the additional assumption that all receiving elements are uniformly distributed over a grid (either in a single row, or in a 2-dimensional plane). This is covered in this Annex as well.

Although these assumptions limit the degrees of freedom with which the antenna array can be designed, they can be used to provide an intuitive overview as to how the list of factors influence the radiation pattern of the antenna array (and their practical implications). Although the validity does not always hold for more complex (non-uniform, diverse, etc.) antenna array configurations, they can still provide an intuitive rule-of-thumb in most cases.

F.2 One-dimensional array

In order to illustrate some of these aspect we consider a one-dimensional array with antenna elements spaced along the x-axis, with inter-element spacing d_x. This configuration is shown in Figure F.1.

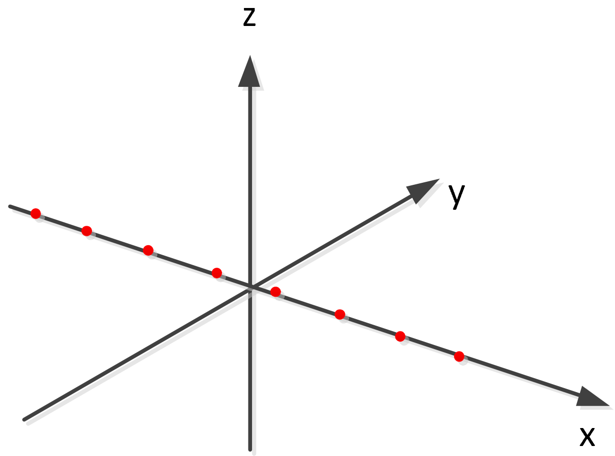

Figure F.1: One-dimensional antenna array

Compared to the case of a planar array, this array only allows for beam forming a single direction. This does not affect the effects with respect to the array properties which are illustrated in the remainder of this section.

F.2.1 Inter-element spacing

Solving the optimization problem to find the optimal set of weights for the signal summation that maximizes the signal response in a certain direction does not necessarily imply that this is the only direction from which the signals are maximized. For an antenna element spacing greater than half the wavelength ($d_{x,y} \geq \lambda/2$) grating lobes will be present in the steering vector. Grating lobes are peaks in the radiation pattern of the steering vector which are equal to the gain in the direction of the main beam. This is shown in Figure F.2.

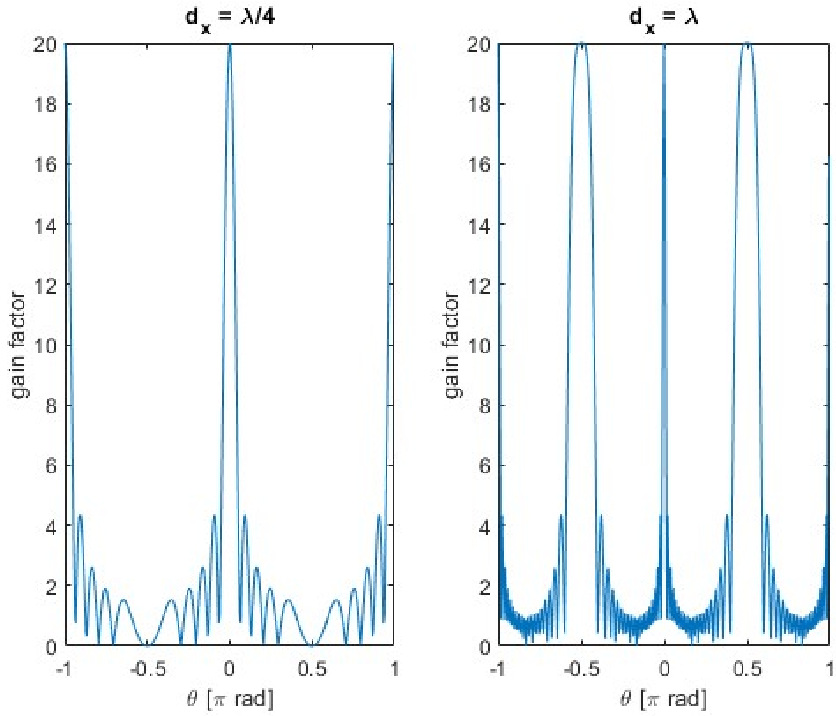

Figure F.2: Effect of element spacing on the presence of grating lobes

It is clear that the presence of grating lobes can have a significant effect on the total signal response of the antenna array system. Grating lobes can lead to interference from signal that originate from directions other than the direction of the desired signal source.

F.2.2 *Array dimensions*

The dimensions of the array configuration can be viewed as a sort of equivalent antenna aperture for the array system. For uniformly distributed arrays this implies that the antenna dimensions are determined by the number of elements, and their inter-element spacing d_x (and d_y for planar array configurations).

As such the array dimensions influence the minimum beam width that can be achieved by the steering vector. The larger the aperture, the more narrow the beams are that can be formed. This is illustrated in Figure F.3.

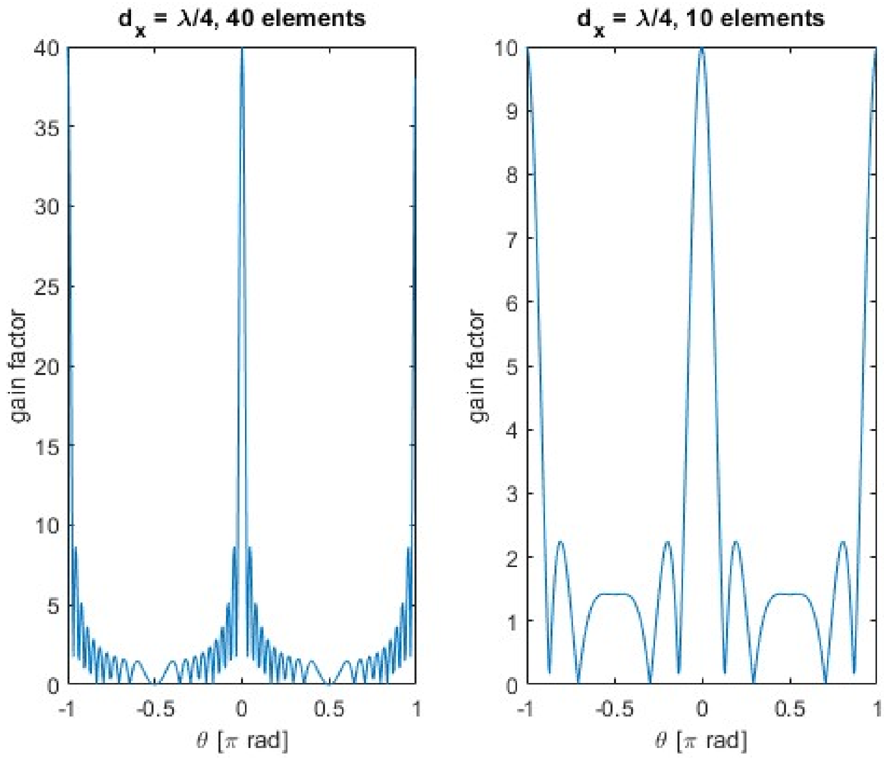

Figure F.3: Effect of array dimensions on the beam width

F.2.3 Antenna type

The total directional response of the array system is determined by the steering vector radiation pattern, multiplied by the radiation pattern of the antenna element. Given (20) (but then reduced for a one dimensional array) it can easily be seen that the effect of grating lobes is especially significant for antennas whose radiation pattern is more or less equal in for all values of θ, such as omni-directional antennas.

For highly directive antennas the total signal response from the directions of the grating lobes are attenuated since they coincide with the locations of small sidelobes in the antenna element radiation pattern. Nevertheless, the grating lobes still lead to an increase of the response from the sidelobe directions.
Furthermore the physical dimensions of each antenna type needs to be considered. Especially for very small wavelengths it can very well be that the physical dimensions of each antenna elements are greater than the desired spacing of less than half a wavelength. This makes an antenna configuration without grating lobes often impossible.

F.3 Possible array configuration to be considered

In this section two antenna arrays are considered. The first configuration is based on a uniformly distributed planar array antenna whose elements are sufficiently small to allow for an inter-element spacing of less than half a wavelength. The other configuration is based on an array of highly directional antennas with a very large inter-element spacing because of their physical dimensions.

F.3.1 *Concept 1: Patch antenna based array configuration*

One antenna type that meets the dimensional conditions to allow a small inter-element spacing is the patch antenna. Antenna array configurations with beam steering capabilities are already employed in operational radar systems such as the Active Phased Array Radar (APAR).

Although this model provides the best performance in terms of beam steering capabilities, the gain of each element is quite small as a result of their minimal directivity. A very large array using this antenna type may be required provide sufficient gain in the direction of interest to receive the desired signal (depending on the required antenna sensitivity requirement of the receiving system).
As can be seen from Figure F.4, the radiation from such an antenna array is mainly steered in the direction orthogonal to the plane in which the array configuration is defined. In a final practical implementation a very large antenna array based on this concept may be mounted on a structure which allows mechanical rotation and tilting, providing the option to steer the array in the desired direction.

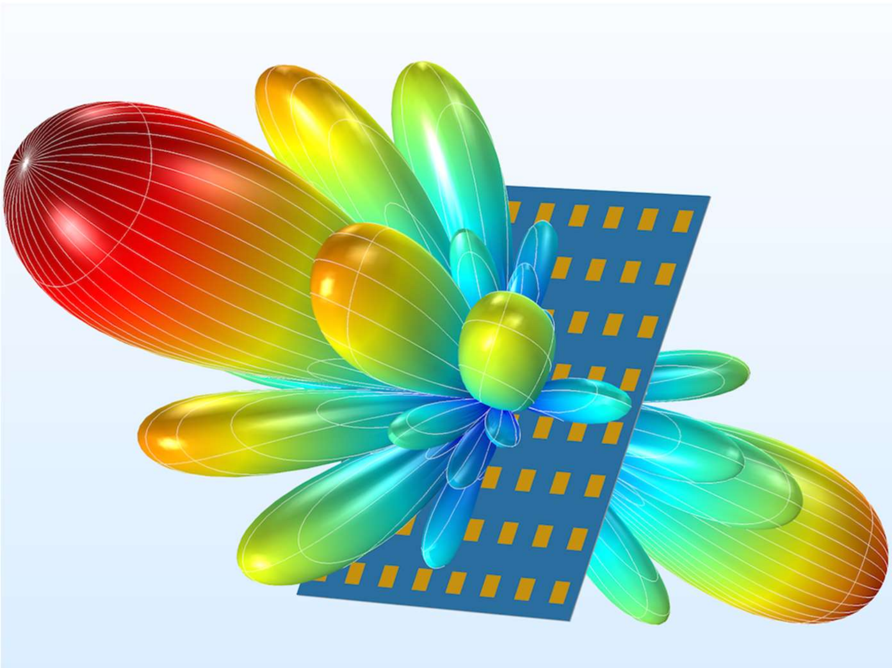

Figure F.4: Conceptual image of a patch antenna array

F.3.2 *Concept 2: Array based on highly directional antennas*

On the other end of the spectrum an antenna array using highly directive antenna types can be employed. These antenna types, such as the parabolic reflector antenna, often do not meet the dimensional requirements to allow for a half wavelength inter-element spacing.

However, thanks to the high directional gain of each element a smaller number of elements may be required to provide the receiver sensitivity needed to receive the desired signal. Since in such a configuration the antenna elements are spaced quite far apart the dimensions of such an array allow for a large effective aperture with fewer antenna elements. In the field of radio astronomy this configuration is often employed to receive weak signals from space.
Such a configuration comes however with quite a few challenges.

1. The synthetisation problem to design an array configuration which meets the beam steering requirements is very complex and needs a very detailed study;
2. Since the receiver elements are spaced far apart the assumptions which allow for the definition of a less complex model become very weak, therefore requiring the use of a more complex model;
3. Where in the field of radio astronomy most antenna elements are directed towards the sky, this is most of the time not the case when the array is used to receive or filter out signals at low elevation angles. In this case the physical dimensions of the antenna may lead to signal blockage for other antenna elements, therefore limiting the possible array configurations which can be used.

F.4 Background: Beam steering

This background section annex is focused on formulating the theoretical background to model the beam steering/spatial filtering capabilities of (mainly planar) antenna array configurations. After defining the reference frame in which the model is formulated a representation will be defined which aims to provide complete overview of the full set of received signals at each receiving antenna element. It will be shown that the response at each element is defined mostly through the location of the antenna element (with respect the centre of the reference frame, relative to the transmitter location), and the radiation properties of the antenna element itself. From the detailed overview a more simple model will be derived which aims to decouple the antenna properties of each element from the antenna array geometry, reducing the radiation pattern of the antenna array to the multiplication of the radiation pattern of a single element with an ‘array factor’ (AF). This allows for a reduced problem statement in which only the angles of maximum and minimum (‘null steering’) radiation are specified. Additionally, the simplified model allows for an intuitive analytic solution which can be used to give rudimentary insight in the beam steering potential of an ‘ideal’ array configuration.

F.4.1 Reference frame

The locations source and receive elements within the array models are defined within some right-handed Cartesian reference frame by their position (or radius) vector

$$\boldsymbol{p} = [x\ y\ z]^T \tag{1}$$

with respect to the reference origin O, or alternative in terms of their spherical coordinate representation

$$\boldsymbol{p} = [r\ \theta\ \phi]^T \tag{2}$$

as depicted in Figure 5.

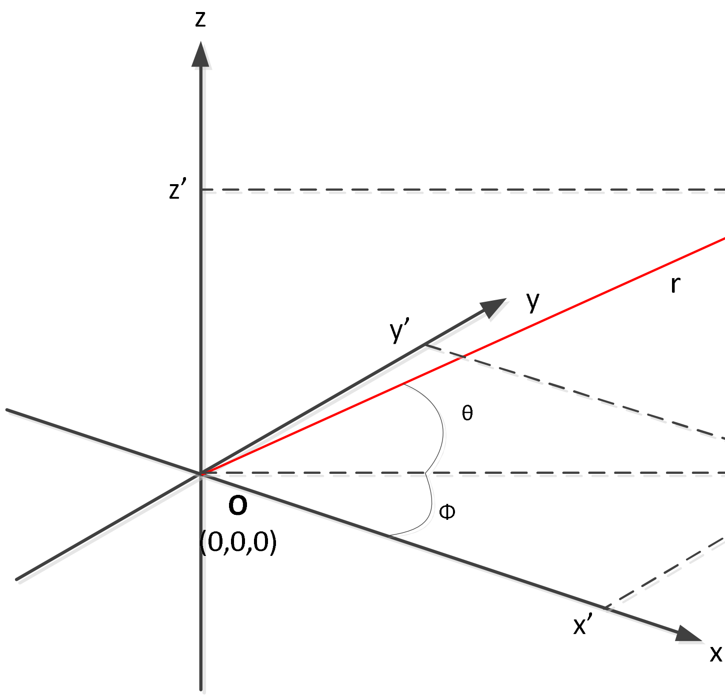

Figure F.5: Reference frame in terms of Cartesian coordinates (x,y,z) and spherical coordinates (r,θ, ϕ)

The position of the signal source is denoted by position vector $\boldsymbol{p_s}$, whereas receiver locations are denoted by $\boldsymbol{p_i}$. Alternatively locations can be described relative to some other point within the reference frame as shown in Figure F.6. Here the notation with an apostrophe is used to denote the location of a receiver elements with respect to source point $\boldsymbol{p_s}$.

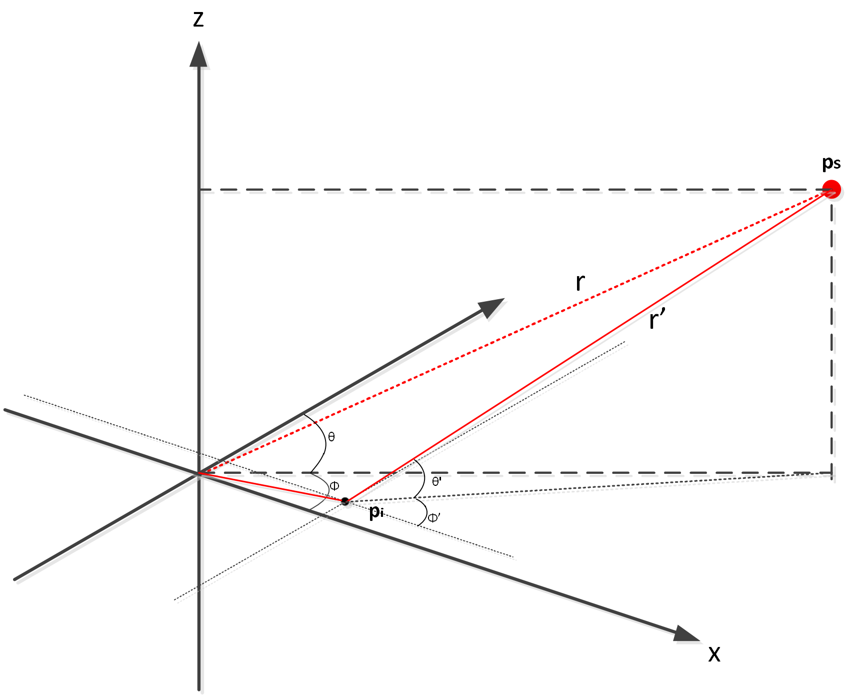

Figure F.6: Location coordinates relative toward a point other than origin 0

F.4.2 Complete array model

The configuration that is used to model the antenna array behaviour is shown in Figure , where all N receiving elements $\boldsymbol{p_i}$ ($\{1 \leq i \leq N; N \in \mathbb{Z}\}$) are placed at a location within the $x-y$ plane. The source antenna given by point $\boldsymbol{p_s}$ is located somewhere in the $x-y-z$ space, but outside the boundaries of the antenna array

$$x_s \in \mathbb{R} \;\backslash \arg\min_i(x_i) \leq x_s \leq \arg\max_i(x_i) \tag{3}$$

$$y_s \in \mathbb{R} \;\backslash \arg\min_i(y_i) \leq y_s \leq \arg\max_i(y_i) \tag{4}$$

$$z_s \in \mathbb{R} \tag{5}$$

Additionally, the source is located sufficiently far away from each of the receiving elements with respect to the wavelength of the signal

$$r_i' \gg \lambda \tag{6}$$

such that far-field conditions are applicable. As will be shown in the following section this provides the basis for the complexity reduction in the simplified model. For now this assumption allows the received signal $x_O(t)$ at the origin O to be modelled as a plane wave

$$x_O(t) = A_0 e^{-j(2\pi f t + \psi_O)} \tag{7}$$

with A_0 some initial signal amplitude, f the frequency in Hz, ψ_O a random phase offset uniformly distributed in the range $0 \leq \psi_O \leq 2\pi$.
An example of a possible antenna configuration is shown in Figure F.7 for the special case of where all receiving elements are uniformly spaced within a grid structure. Although this is configuration is not unusual, the (complete) model in this section is not limited to such ordered configurations.

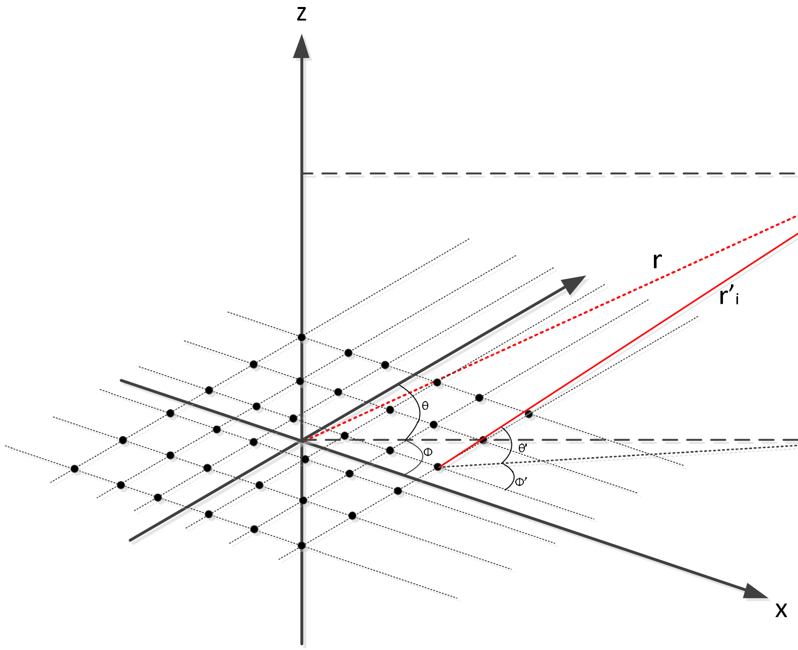

Figure F.7: Planar uniformly distributed antenna array configuration

The complete set of signals received at the N antenna elements within the array, distributed along the x-y plane, is then modelled using $\boldsymbol{x}(t,\theta)$, given by

$$\boldsymbol{x}(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_N(t) \end{bmatrix} = x_O(t) \begin{bmatrix} a_{r_1} e^{j\psi_{r_1}} \times g_{a_1}((\theta,\phi)_1) e^{j\psi_{a_1}((\theta,\phi)_1)} \\ a_{r_2} e^{j\psi_{r_2}} \times g_{a_2}((\theta,\phi)_2) e^{j\psi_{a_2}((\theta,\phi)_2)} \\ \vdots \\ a_{r_N} e^{j\psi_{r_N}} \times g_{a_N}((\theta,\phi)_N) e^{j\psi_{a_N}((\theta,\phi)_N)} \end{bmatrix}$$
$$= x_O(t)\boldsymbol{u}(\boldsymbol{p_i},\theta_i,\phi_i) \qquad (8)$$

with

- $a_{r_i} e^{j\psi_{r_i}}$
  a complex gain/attenuation factor which accounts for *relative* signal loss and phase offsets *between the receiving elements* due to the *difference* distance between the receiving elements relative to origin O;
- $g_{a_i}((\theta,\phi)_i) e^{j\psi_{a_i}((\theta,\phi)_i)}$
  a complex gain/attenuation factor which accounts for the directional dependence of the antenna element (radiation pattern);
- $\boldsymbol{u}(\boldsymbol{p_i},\theta_i,\phi_i)$
  The steering vector being dependent on the antenna element configuration.

The relative phase offset is given by

$$\psi_{r_i} = \boldsymbol{k_i} \cdot \boldsymbol{p_i} \qquad (9)$$

With $\boldsymbol{k}$ the wave vector defined by the signal wavelength λ, and the angle of incidence of the plane wave with respect to the location of the antenna element (defined in terms of elevation angle θ and azimuth ϕ), and $\boldsymbol{p}_i$ the location of the antenna element within the Cartesian reference frame. As given by

$$\boldsymbol{k_i} = \frac{2\pi}{\lambda}\,[sin(\theta_i)\,cos(\phi_i) \quad sin(\theta_i)\,sin(\phi_i) \quad cos(\theta_i)] \tag{10}$$

$$\boldsymbol{p_i} = [x_i \quad y_i \quad z_i]^T \tag{11}$$

the phase offset at location $\boldsymbol{p_i}$ can be expressed as

$$\psi_{r_i} = \frac{2\pi}{\lambda}(\sin(\theta_i)\cos(\phi_i)x_i + \sin(\theta_i)\sin(\phi_i)\,y_i) \tag{12}$$

were the fact that $z_i = 0$ is already taken into account.

F.4.3 *Simplified model: far-field reduction*

As mentioned in the previous section the signal source is located in the far-field (with respect to every antenna element). This far-field condition allows for a number of assumptions with respect to (8) which can be used to reduce the complexity of the model:

1. Signal amplitude variations between the receiving elements due to the difference distance from the source can be neglected. Therefore, the amplitude at each the receiving elements is assumed equal to the signal amplitude at the origin
$$a_{r_1} \cong a_{r_2} \cong \cdots \cong 1 \tag{13}$$
2. The angle of incidence with which the transmitted signal arrives at each of the receiving elements can be neglected. Therefore the angle of incidence at each of the receiving elements is assumed to be equal to the angle of incidence at the origin O
$$\theta'_1 \cong \theta'_2 \cong \cdots \cong \theta \tag{14}$$
$$\phi'_1 \cong \phi'_2 \cong \cdots \cong \phi \tag{15}$$
3. All antenna elements are of the same antenna type, therefore the radiation pattern for each of the antenna elements is the same
$$g_{a_1}(\theta,\phi)e^{j\psi_{a_1}(\theta,\phi)} \cong g_{a_2}(\theta,\phi)e^{j\psi_{a_2}(\theta,\phi)} \cong \cdots \cong g_{a_N}(\theta,\phi)e^{j\psi_{a_N}(\theta,\phi)} \tag{16}$$

It should be noted that the assumptions 1 and 2 become weaker as the distance between the antenna elements increases. Also, assumption 3 further weakens (when assumption 2 weakens) when the antenna elements can be mechanically rotated with respect to each other.
Assumptions 1, 2 and 3 allow for a decoupling of the antenna specific parameters (i.e. the radiation pattern of the receiving elements) to be decoupled from the array configuration, leaving only the phase difference ψ_{r_i} between the receiving elements as the differentiating factor. The simplified model is then given by

$$\begin{aligned}\boldsymbol{x}(t,\theta,\phi) &= x_O(t)g(\theta,\phi)e^{j\psi(\theta,\phi)}\begin{bmatrix} e^{j\psi_{r_1}} \\ e^{j\psi_{r_2}} \\ \vdots \\ e^{j\psi_{r_N}} \end{bmatrix} \\ &= x_c(t,\theta,\phi)\boldsymbol{u}(\boldsymbol{p_i},\theta,\phi)\end{aligned} \tag{17}$$

Note that in $\boldsymbol{u}(\boldsymbol{p_i},\theta,\phi)$ the number of variables which define the steering vector has decreased from $2N$ different angles of incidence θ_i and ϕ_i to only 2 different angles of incidence with respect to the origin.

F.4.4 *Beam steering*

Now that the signal at each of the array elements can be characterized using an antenna dependent factor and a steering vector $\boldsymbol{u}$ the total response from the antenna array as a system can be explored. This response is defined as the sum of all individual responses, multiplied by a weighing factor w_i per antenna element, as

$$s(t) = \boldsymbol{x}(t)\boldsymbol{w}^* = \sum_{i=1}^{N} x_i\,(t)w_i^* \tag{18}$$

where $(\cdot)^*$ denotes conjugate transpose. The vector $\boldsymbol{w}$ denotes a weighting vector to be used in the summation of the signals each antenna element.
Inserting the representation for the simplified model (17) in (18) gives

$$s(t) = x_O(t)g(\theta,\phi)e^{j\psi(\theta,\phi)} \sum_{i=1}^{N} w_i^* e^{j\psi r_i} \tag{19}$$

then using (12)

$$s(t) = x_O(t)g(\theta,\phi)e^{j\psi(\theta,\phi)} \sum_{i=1}^{N} w_i^* e^{j\frac{2\pi}{\lambda}\sin(\theta)\cos(\phi)x_i}\, e^{j\frac{2\pi}{\lambda}\sin(\theta)\sin(\phi)y_i} \tag{20}$$

Using (20) an optimization problem can be defined to find the set of weighting vectors $\boldsymbol{w}$ and antenna locations $\boldsymbol{p_i}$ such that the response is maximized for signal originating from a certain angle of incidence (θ, ϕ), or alternatively zero.
Whilst the antenna locations influence the radiation patterns in a static fashion, the weighting vector can changed dynamically in order to provide electronic beam steering capabilities to the antenna array.
Finding the solution of to such a problem is studied extensively in the area of array pattern synthesis. However, for antenna arrays which are uniformly distributed along a grid an analytic solution can be found which can be used to illustrate some aspects related to beam steering capabilities.

F.5 Uniform planar arrays

In such an antenna array al elements are distributed evenly along the x and y axis in a fixed grid. The element spacing between elements in the x and y direction can however be different.
For an array with N elements spaced d_x (no unit, often normalized with respect to wavelength) and M elements space d_y apart, it can be shown that the steering vector $\boldsymbol{u}$ has the can be expressed as

$$\boldsymbol{u}(\theta,\phi) = \left\{\frac{1}{M}\frac{\sin\left(\frac{M\psi_x}{2}\right)}{\sin\left(\frac{\psi_x}{2}\right)}\right\}\left\{\frac{1}{N}\frac{\sin\left(\frac{N\psi_y}{2}\right)}{\sin\left(\frac{\psi_y}{2}\right)}\right\} \tag{21}$$

With fixed phase offset β_x and β_y in the weighting vector as

$$\psi_x = \frac{2\pi}{\lambda} d_x \sin(\theta)\cos(\phi) + \beta_x \tag{22}$$

$$\psi_y = \frac{2\pi}{\lambda} d_y \sin(\theta)\cos(\phi) + \beta_y \tag{23}$$

From here the phase offsets that provide a maximum response in the steering vector from direction (θ_0, ϕ_0) are then given by

$$\beta_x = -kd_x \sin(\theta_0)\cos(\phi_0) \tag{24}$$

$$\beta_y = -kd_y \sin(\theta_0) \cos(\phi_0) \tag{25}$$

Although the uniformly distributed antenna array seems to provide quite a convenient solution, there are still some caveats that need to be considered. The full response in all directions θ and ϕ is defined by the inter-element spacing d_x and d_y. While the solutions to β_x and β_y provide convenient means to maximize the received signal strength from one direction, this does not necessarily mean that this is the only direction from which the received signal strength is maximized.

G External academic appreciation

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dr. ir. P.D.C. (Peter) Anker
Ministerie van Economische Zaken en Klimaat

Datum
5 november 2018

Dear dr. Anker,

Through this letter I would like to offer an academic appreciation of the scientific aspects of the TNO research report "Co-existence of 5G mobile networks with C-Band Satellite Interception in Burum", project number 060 33165.

This report and the results therein are, in my opinion, based on a scientifically sound and thorough analysis. The conclusions and recommendations are derived logically and correctly from the obtained results.

I would like to emphasize that:

- it is fundamentally impossible to make accurate predictions on the co-existence problems between 5G mobile networks and the Burum Interception Facility. This is inherent and not due to shortcomings in the research or report.
- additional measurements or analyses in order to more precisely quantify the results are therefore useless from a scientific point of view.
- the gap between required and expected isolation of the 5G and Burum Interception Facility is so large that the main conclusions of the report are justified despite the inherent uncertainties: a co-existence solution is not possible and any compromise will only provide a temporary work-around involving high costs and strongly reduced performance on both sides (5G and Burum Interception Facility).
- the midterm and long term performance of the Burum interception facility will significantly decrease because of introduction of 5G in neighbouring countries, even if 5G would not be introduced in the Netherlands at all.

I hope that this letter provides a useful contribution to the research and report. Please feel free to contact me if there are any questions or comments.

Sincerely,

Peter Baltus

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Appendix:
Explanation and supporting arguments for academic appreciation

My academic appreciation, as presented in the body of this letter, is based on:

- the study of the TNO research report "Co-existence of 5G mobile networks with C-Band Satellite Interception in Burum", project nummer 060 33165,
- attending the kick-off, midterm and final meeting of the "begeleidingscommissie TNO-onderzoek Impact 5G-netwerken op Burum" on June 29th 2018, August 31st 2018 and September 28th 2018
- an introductory meeting with A.H. van den Ende (TNO) on June 14th 2018
- knowledge and insights obtained in the course of my career

I've examined a number of specific aspects which I would like to explain in more detail in this appendix. These aspects significantly contributed to my academic appreciation of the research report.

Uncertainties
Uncertainties play an important role in this study. In general, three types of uncertainties can be distinguished:

1. Uncertainties caused by implicit (and therefore not explicitly verified) assumptions. These uncertainties can be reduced by explicitly stating and evaluating these assumptions.
2. Uncertainties caused by limited accuracy of the models that have been used in the study. These uncertainties can be reduced by developing more accurate models – at the cost of time, effort and complexity. This does not imply that this is always useful.
3. Uncertainties caused by important factors that are inherently unpredictable. These uncertainties cannot be reduced through extra efforts or increased complexity. They can only be analyzed based on scenarios and statistical modeling.

In this report, all three types of uncertainties are relevant:

1. Uncertainties of type 1 are in practice less important than they might seem since experienced researchers such as the authors of this report are very well capable to select assumptions that significantly contribute to the conclusions and their (un)certainties, and subsequently to thoroughly evaluate the most important assumptions.
   For example: an implicit assumption is that 5G technology will work sufficiently well in practice to be attractive for users. This has already been extensively tested in various field labs, test setups, simulations etc. If there would still be significant shortcomings in the system then it is highly likely that they will be solved by improving the 5G system or its successors.
   Another implicit assumption is that there won't be major changes in the world that would make "5G" or "Burum" superfluous. If this would happen then it would be very likely that the major consequences of such changes would have a major impact on our society, such that co-existence between radio systems are likely to be considered relatively unimportant. In this report, I have not identified implicit assumptions that would justify a further evaluation.
2. Models are virtually always inaccurate: the reason to use models is that they result in insights or a faster/more efficient analysis, both of which require a reduction of complexity and therefore a reduction in accuracy with respect to reality. In this analysis this is especially relevant for the modeling of propagation: replacing multiple 5G base stations by one combined signal source is an approximation, categorizing areas in

specific classes is an approximation etc. The consequences of these inaccuracies and uncertainties have been analyzed for a set of specific cases and shown to be limited. In theory it's possible that the cases that have been analyzed are not representative for a number of important interferer sources, but there are no indications in this report or in the literature that I'm aware of which would make this a likely scenario. Moreover, it is important to consider that the uncertainties of type 3 (below) can be expected to have a much larger impact on the outcome of the report than inaccuracies in modeling. For example: changes in buildings (new buildings, demolition or refurbishing of existing buildings, growing or removing trees) and propagation (such as changes in the ionosphere caused by climate change). Inaccuracies in the models are discussed extensively in this report and are shown to be far smaller than required to change the conclusions of the report.

3. Uncertainties of type 3 are e.g. the development of 5G in the Netherlands and surrounding countries, the types of base stations that will be used, the exact properties of new applications that might be based on 5G, the intensity of 5G usage as a function of location and time, and many other aspects, many of which are explicitly mentioned in the report. These uncertainties usually depend in a complex way on unpredictable processes, such as the introduction and popularity of new applications, acquisitions of operators by other companies that cause abrupt changes in strategy, economic developments etc. As shown in the report as part of te analysis of various scenarios for the development of 5G, the consequences for interference of 5G and Burum are very large, even though none of the scenarios can be dismissed at this time.
   The uncertainties of type 3 and their impact are much larger than those of type 2. I'm especially worried about the introduction of new applications that cannot be predicted yet. There are many examples in the history of wireless technology where new applications unexpectedly and abruptly became very popular (e.g. SMS text messages, wireless headphones, and smartphones). This unpredictability and the difficulties in managing or limiting popular wireless applications once they are in widespread use make this an important uncertainty. Even new regulations are often insufficient to eradicate unexpectedly popular applications (e.g. illegal CT0 cordless phones that were illegally important into the Netherlands and afterwards had to be legalized in some form). A possible (but currently not foreseeable) example could be peer-to-peer 5G applications between mobile terminals (cars, smartphones etc.) that would operate without requiring base stations (even if only in a fallback mode). This could make enforcing an exclusion zone around Burum impractical or even impossible.

The only addition that could be useful from a scientific and methodological point of view would be a sensitivity analysis to quantify the impact of various uncertainties. The differences between the three types of uncertainties and their impact are so large that I can't imagine that this would result in a different conclusion than in the current version of the report.

Compromise
The conclusion that a compromise is unavoidable since the no solution can be found that would not result in large costs and simultaneously important performance reductions is logical and scientifically valid.
There are an infinite number of possible compromises with different balances in cost and performance of both systems. The selection of a compromise would most likely be based on both technical and non-technical considerations.

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Datum
5 november 2018

Pagina
4 van 4

Especially the non-technical considerations, such as the relative importance of both systems, are difficult to quantify and are outside the scope of this report and outside my area of expertise. The compromises that are discussed in this report should therefore (as indicated in the report) be considered as examples rather than as a proposal.

H Assessment anti-competition aspects

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4 december 2018

Betreft: Ordernummer 1300027084
- aanbieding volledig TNO rapport voor toetsing

Geachte heer Van den Ende,

Overeenkomstig de opdracht van het Ministerie van Economische Zaken en Klimaat van 30 juli 2018, hebben wij een mededingingsrechttoets uitgevoerd op het door u op 16 november 2018 aangeleverde conceptrapport "*Co-existence of 5G mobile networks with C-Band Satellite Interception in Burum*". Doel van de toets is te voorkomen dat – als gevolg van de openbaarmaking van het rapport – door individuele mobiele operators aan TNO overhandigde informatie op een met het mededingingsrecht strijdige wijze met andere operators zou worden gedeeld.

Bij het uitvoeren van de toets zijn wij uitgegaan van de ons door TNO aangereikte informatie en stukken. Naast de hiervoor genoemde conceptrapportage ontvingen wij op 15 oktober 2018 in concept twee door u in verband met de onderhavige opdracht relevant geachte hoofdstukken van het rapport, alsook een door TNO op 12 juni 2018 aan de betrokken mobiele operators toegezonden "*Questionnaire on 5G deployment aspects*". Voorts zijn door u op 18 oktober 2018 telefonisch enkele vragen van onze kant aangaande de hiervoor genoemde concepthoofdstukken beantwoord.

CMS

Wij kunnen bevestigen dat wij in het ons voorgelegde concepteindrapport van TNO geen tot een individuele mobiele operator herleidbare en van laatstgenoemde afkomstige concurrentiegevoelige informatie hebben aangetroffen die als gevolg van het openbaar maken van het rapport op een met het mededingingsrecht strijdige wijze met andere operators zou worden gedeeld.

Met vriendelijke groet,

Robert Bosman

Simon Sanders