

Assessing the capacity, coverage and cost of 5G infrastructure strategies: Analysis of the Netherlands

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ABSTRACT

Many of the technologies driving both the global economy and societal development, such as the Internet of Things, Industry 4.0 and Smart Healthcare, depend on adequate capacity and coverage of digital connectivity. It is therefore essential that wireless connectivity can be delivered in a cost-efficient way by Mobile Network Operators, for the benefit of all digital ecosystem actors. The contribution of this paper is to analyse the capacity, coverage and cost of different enhanced Mobile Broadband (eMBB) infrastructure strategies, as the industry moves towards integrating new 5G spectrum bands and densifying existing networks. Both a supply-driven and demand-driven investment analysis is undertaken using a case study of the Netherlands. The supply-driven analysis estimates the capacity that can be provided to users via new spectrum, before network densification via small cells is required. The demand-driven analysis tests a range of required per user speeds including 30, 100 or 300 Mbps and quantifies the performance of investment strategies in meeting this demand. The key contribution is estimating the traffic threshold delivered per user from integrating 5G spectrum bands on the existing Dutch macrocell network. Based on the inputs of this analysis, we find that 5G spectrum bands provide an average per user traffic capacity improvement of approximately 40% for the Netherlands in comparison with the existing LTE capacity.

1. Introduction

In many telecommunications markets across the globe, operators have been experiencing flat or declining revenues for multiple reasons. Firstly, a shift in the use of communication services has seen consumers move away from traditional voice and SMS, to using Voice over IP (VoIP) and texting applications (e.g. Skype, WhatsApp etc.). Secondly, there has been strong sectoral regulation in many European countries leading to an increasingly competitive market due to new traditional and virtual Mobile Network Operators (MNOs) (Ghezzi et al., 2015). Additionally, the mobile broadband market expedited by the launch of the Apple iPhone in 2007 has begun to saturate due to near-universal adoption. Indeed, this situation is challenging because of the huge increase in the demand for mobile data, driven by the increasing use of video content (and other media) on smartphones (West and Mace, 2010; Cisco, 2017). Therefore, decision-makers within the telecoms sector increasingly require new analytics to navigate this challenging landscape.

Telecommunications are essential for the modern digital economy. Without adequate and sufficient connectivity, we will not be able to realise the economic and societal benefits associated with myriad technological solutions. Indeed, wireless communications is the bedrock of the smart movement, predicated on the pervasive embedding of ICT devices into the physical environment. This includes the Internet of Things (Chen et al., 2014; Whitmore et al., 2015; Thibaud et al., 2018), Smart Cities (Caragliu et al., 2011; Kuk and Janssen 2011; Bresciani et al., 2017), Smart Infrastructure (Hoult et al., 2009; Borlase, 2016), Smart Healthcare (Chatterjee et al., 2009; Pramanik et al., 2017; Yang et al., 2018; Hemaury et al., 2018), and Industry 4.0 (Lee et al., 2015; Wang et al., 2016;

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<https://doi.org/10.1016/j.tele.2019.01.003>

Received 20 July 2018; Received in revised form 20 October 2018; Accepted 4 January 2019

Available online 06 January 2019

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Brunet-Thornton and Martinez, 2018; Li et al., 2017). To ensure these technologies can be enabled, we must ensure the supply of digital connectivity can respond in a cost-effective way to the increasing data demand created by new content, applications and services.

This relatively bleak economic landscape sits as the telecommunications industry is gearing up for the rollout of the next generation of mobile communication technology known as ‘5G’. The successor of the Long Term Evolution technology (4G), 5G, is expected to deliver significant horizontal and vertical change across the telecoms sector via three main use cases including Enhanced Mobile Broadband (eMBB), Massive Machine-type Communications (mMTC), and Ultra-Reliable and Low-Latency Communications (URLLC). Supply-side improvements to both the Radio Access Network (RAN) and the core will utilise high frequency (Millimetre Wave) bands, Massive MIMO/beamforming, Device-to-Device communications, Network Function Virtualisation (NFV) (cloud-based network), Software Defined Networks (SDN) and Massive Machine Communication (Andrews et al., 2014; Wong et al., 2017). This is expected to provide higher data rates, lower latency and enable a dramatic increase in the number of devices per square kilometre (International Telecommunication Union, 2015). Although 4G has been used for IoT uses, it faces numerous challenges as the number of node connections increases, requiring 5G technologies. Network densification will be a dominant theme in the evolution of wireless communications into 5G (Bhushan et al., 2014). Hence, the deployment of 5G networks will require additional investment to upgrade mobile communication infrastructure to provide the desired technical specifications of the standard. A key development is delivery to the demand-side using network slicing, where heterogeneous communications services can be supplied to specific industrial use cases, with the potential to enable widespread digital transformation across society and the economy (Cave, 2018).

It is expected that mobile traffic demand across communication networks will continue to increase dramatically, requiring upgrades to be rolled out across existing mobile networks. Some proposed key end-uses include gigabit access, as well as data-intensive applications which include seamless HD video-on-demand, Virtual Reality (VR), Augmented Reality (AR), and gaming (Bastug et al., 2017; Ge et al., 2017; Erol-Kantarci and Sukhmani, 2018). All these examples are driving the demand for increased capacity and coverage. Some of the newer applications such as e.g. VR and AR are expected to consume far larger amounts of bandwidth than current applications. Indeed, to support this traffic in an affordable way, 5G networks must deliver data at much lower cost per bit compared to the networks of today.

Currently, there is limited knowledge and understanding of the financial impacts of the rollout of different 5G infrastructure strategies which we define as (i) integrating new 5G spectrum bands on existing sites with multi-carrier capabilities (a ‘spectrum integration’ approach), (ii) densifying the radio network with smaller cells (a ‘small cell’ approach), or (iii) a combination of both (a ‘hybrid’ approach). Consequently, we focus on undertaking both a supply-driven and demand-driven investment analysis, assessing the capacity, coverage and cost of eMBB infrastructure-expansion strategies. The supply-driven approach examines the per user capacity that can reasonably be delivered, whereas the demand-driven analysis targets the delivery of 30, 100 or 300 Mbps per user. The following set of research questions are posed:

1. What is the potential traffic level that would trigger the need to deploy small cells?
2. For different expansion strategies what are the key cost components?
3. What is the cumulative cost of covering different proportions of the population?
4. How do different strategies perform in meeting demand?
5. What are the investment costs per user?

A literature review is now undertaken to define 5G and position the paper within the wider techno-economic analysis of wireless networks. The methodology will then be presented in Section 3, with the results reported in Section 4. Finally, we discuss and reflect on the effectiveness of the analysis in Section 5, concluding in Section 6.

2. Literature review, related work and theoretical background

This section undertakes a literature review which focuses on new 5G technical developments, service use cases, the 5G architecture, and discussing relevant research on the techno-economic analysis of wireless networks.

2.1. What is 5G?

One of the prominent new capabilities is the use of millimetre wave (mmWave) frequency bands for transmission between roughly 30–300 GHz for mobile communications. Higher data capacity rates are promised using mmWave than currently available, due to the larger bandwidth in this part of the electromagnetic spectrum. Also, the antennas used to transmit and receive the signals can be made comparably smaller due to the shorter wavelengths. The challenge for mmWave will be the reduced propagation that come with these higher frequencies. Other new capabilities that are expected of 5G technology also include:

- New waveform that adapts the OFDM-based LTE air interface to be suitable for the new use cases.
- The use of massive multiple-input multiple-output (MIMO) beamforming antennas as higher frequencies are significantly more affected by propagation path loss requiring increased compensation by higher antenna gains. Additionally, adaptive beamforming algorithms, even on a per-device basis, are required and can be implemented using active antenna technology.
- Device-to-device (D2D) communications making it possible for devices to communicate directly with each other without direct involvement from the mobile network. This is already an existing use case for LTE to satisfy requirements from the public safety

sector. D2D communications also provide low latency for specific scenarios.

- Network Function Virtualisation (NFV) where the aim is to deploy dedicated hardware functions as virtualised software on general-purpose hardware (i.e. servers) in the core network. This is extended to the radio network by separating base stations into radio units and baseband units (connected via fibre).
- Splitting the control of the user plane and/or decoupling the downlink and uplink ('slicing'). The focus is on heterogeneous network deployments, making it possible to control all user devices on a macro layer, whereas user data is independently provided via a small cell.
- The use of light MAC and optimised radio resource management (RRM) strategies where scheduling strategies would potentially require leaner protocol stacks deployed in uncoordinated scenarios.
- Frequency Division Duplex (FDD) has been the dominating duplex arrangement since the beginning of the mobile communication era. In the 5G era, FDD will probably remain the main duplex scheme for lower frequency bands, also for historical reasons. However, for newer allocated higher frequency bands targeting very dense deployments, Time Division Duplex (TDD) will play a more important role. For the dynamic traffic variations expected in very dense deployments, the ability to dynamically assign transmission resources (time slots) to different transmission directions may allow for more efficient utilisation of the available spectrum. To reach its full potential, 5G should, therefore, allow for very flexible and dynamic assignment of TDD transmission resources.

2.2. Service use cases

Enhanced mobile broadband will aid in meeting increasing demand for higher data speeds and larger mobile data volumes. Examples may be gigabit connections to vehicles and trains, data-intensive applications such as video, video-on-demand, streaming and gaming. All these examples are driving the demand for more coverage and capacity. To support this traffic in an affordable way, 5G networks must deliver data at a much lower cost per bit compared to the networks of today. Furthermore, the increase in data consumption will result in an increased energy footprint. 5G must, therefore, consume significantly less power per delivered bit than current cellular networks to make enhanced mobile broadband a reality.

Massive Machine-type Communications (mMTC) refers to services that typically span very large numbers of devices, such as sensors and actuators. Sensors are low-cost devices and consume very low amounts of energy to sustain a long battery life. The amount of data generated by each sensor is typically very small and will individually have limited impact on the overall traffic volume of a mobile communication network. However, there may be a significant impact if millions or even billions of individual sensors are deployed. In terms of technical requirements, very low latency is not a critical requirement for MTC. There is much to gain from a network being able to handle as many different applications as possible, including mobile broadband, media delivery and a wide range of MTC applications by means of the same basic wireless-access technology and within the same spectrum band. This avoids spectrum fragmentation and allows operators to offer support for new MTC services for which the business potential is inherently uncertain, without having to deploy a separate network and reassign spectrum specifically for these applications.

Ultra-Reliable and Low-Latency Communications (URLLC) will help to support mission-critical applications. Some envisioned 5G use cases, such as traffic safety and control of critical infrastructure and industry processes, may require much lower latency compared with what is possible with current mobile-communication systems. On the other hand, low device cost and energy consumption are not as critical as for massive MTC applications. While the average volume of data transported to and from devices may not be large, wide instantaneous bandwidths are useful in being able to meet capacity and latency requirements. To support such latency-critical applications, 5G should allow for an application end-to-end latency below 1 ms, although application-level framing requirements and codec limitations for media may lead to higher latencies in practice. Many services will distribute computational capacity and storage close to the air interface. This will create new capabilities for real-time communication and will allow ultra-high service reliability in a variety of scenarios, ranging from entertainment to industrial process control.

2.3. 5G architecture

One of the fundamental changes in 5G compared to 2G, 3G and 4G is that the network architecture will no longer be a structure of monolithic elements (e.g. MME, HSS, PCRF, SGW, and PGW as in LTE/EPC architecture, and HLR, MSC-S, SMSC, SGSN, GGSN etc. as in UMTS and GSM architecture). Instead, the architecture is based on a network slicing concept that makes use of network virtualisation and 'softwarisation' of the different network elements.

In the 5GPPP's view on 5G Architecture, a 'network slice' is defined as a composition of configured network functions, network applications, and the underlying cloud infrastructure (physical, virtual or even emulated resources, RAN resources etc.), that are bundled together to meet the requirements of a specific use case, e.g., bandwidth, latency, processing, and resiliency, for a specific business purpose.

An infrastructure provider will assign the required resources for a network slice, that in turn realises the relevant service of a service provider's portfolio (e.g., the vehicular URLLC network slice, the factory of the future URLLC network slice, the health network mMTC network slice etc.). This way, a network slice comprises a subset of virtual network infrastructure resources and the logical mobile network instance with the associated functions using these resources.

The network slice is dedicated to a specific tenant (e.g. a service provider) that, in turn, uses it to provide a specific telecommunication service (e.g. eMBB). The decoupling between the virtualised and the physical infrastructure allows for efficient scaling-in/out/up/down of slices. This concept allows for the economic viability of adapting the network on demand to serve specific

requirements.

Network slices will span the whole protocol stack from the underlying (virtualised) hardware resources up to network services and applications running on top of them. Although the infrastructure resources could be shared among several parallel network slices, every provider may use a specific control framework or/and a specific cloud management system, and, in addition, the configuration effort and fine-tuning of the components may be left to users.

From a business point of view, a network slice includes a combination of all the relevant network resources, network functions, and service functions required to fulfil a specific business case or service, including OSS and BSS.

To support network slicing, the management plane of a network creates a group of network-based resources, which connects with physical and virtual network and service functions as needed. For slice operations, the control plane takes over governing of all the network resources, network functions, and service functions assigned to the slice.

2.4. Techno-economic analysis of wireless networks

Migrating from one generation of mobile wireless technology to another is a classic techno-economic problem as MNOs need to assess options regarding which strategic path to take (Kim et al., 1997). This type of assessment is also necessary for both wireless and fixed ICT infrastructure to ensure the development of efficient and effective markets (Henten and Tadayoni, 2016).

Analysis by Feijóo et al. (2016) assesses the infrastructure impacts arising from uptake in generalised mobile data services by undertaking a techno-economic analysis of Spain. The authors find that the mobile industry's traditional virtuous cycle of investment, innovation, and adoption of services based on supply 'push' has been broken and is now being driven by demand-side 'pull' factors resulting from consumers demanding more and more data. Similarly, a techno-economic approach developed by Ovando et al. (2015) undertakes an LTE assessment for rural areas (also in Spain) using a discounted cash-flow model. The results indicate that the socio-economic characteristics of rural areas make demand very sensitive to price, and the existence of other forms of digital connectivity forces lower Average Revenue Per User (APRU). Hence, only very high adoption rates make such a deployment feasible, potentially combined with a passive infrastructure sharing approach to reduce costs.

Frias et al. (2017) apply a techno-economic assessment methodology for the 700 MHz spectrum band, assessing the value of the band based on the reduction of 4G network rollout costs.

Consumer-focused research by Dagli and Jenkins (2016) models consumer utility and willingness to pay, finding that there is a greater preference for unrestrained roaming where users are willing to pay up to 2% more per month for this benefit. Consumers are also willing to pay for increased data rates but not improvements in quality.

In terms of 5G, a scenario-based assessment is undertaken by Oughton et al. (2018) utilising an open-source mobile wireless assessment model for Britain to evaluate the rollout between 2016 and 2030. Forecasts of per-user data growth are developed for the demand-side, and different infrastructure strategies are compared on the supply-side using a capacity margin metric. The results indicate that the growth in data demand is the largest factor driving the demand-side (rather than population growth), and that 5G spectrum strategies generally meet demand until 2025, after which point a capacity deficit begins to grow.

Analysis by Neokosmidis et al. (2017) presents an assessment of several crucial technological and socio-economic issues expected to influence the deployment and market adoption of 5G networks, building off the work of the 5GPPP CHARISMA project. This evaluation employs results from numerous surveys using a Fuzzy Analytical Hierarchy Process (FuzzyAHP) framework, and more specifically pairwise comparison. The findings indicate that out of a range of different factors, the need to deliver greater performance is the key 5G driver, specifically the need to deliver lower latency, higher reliability and improved data rates. Performance was followed by the need to find new market opportunities and deliver enhanced security and privacy.

In general, there has been relatively limited techno-economic assessment of 5G in the existing literature, despite this being necessary to support decision-making, thereby motivating the need to address this current gap.

3. Methodology

We develop a spatially-explicit, general-purpose model which has the potential to be used to address a wide range of questions by modifying market structure, the number of operators, the existing base station network, market share, spectrum portfolios and the existing backhaul infrastructure. The model is used to assess 5G infrastructure strategies following the methodology illustrated in Fig. 1. The following sub-sections describe the key components of the model including the scenario parameters, demand module, capacity-expansion strategies, 'geotype' segmentation, network dimensioning and the cost assessment module. Appendix B contains a more thorough explanation of the method utilised in the network dimensioning calculations.

3.1. Scenario parameters

OpenSignal (2017) reports that the average mobile download speed in The Netherlands ranges from 26 to 34 Mbps depending on the operator (although this estimate is subject to the usual caveat associated with crowdsourced mobile speed data given measurements are not comprehensive and the user device can affect measurements). This broadly correlates with Appendix A which illustrates the existing 4G LTE capacity per square kilometre by postcode sector for the Netherlands.

Hence, we parameterise three different scenarios based on delivering 30, 100 and 300 Mbps per user during the busy hour. These are highly ambitious targets, but worth exploring. Due to commercial sensitivities, we utilise a 'hypothetical operator' for this paper, which we assume to have a 30% market share, thus serving 30% of the generated traffic (this is a simplification for modelling

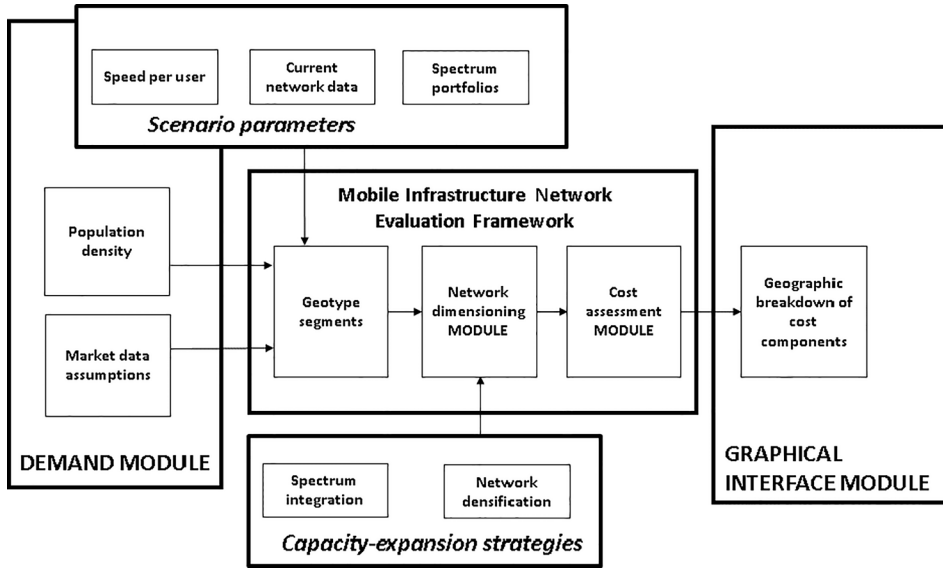


Fig. 1. Modelling methodology and key modules.

purposes, revisited in the discussion).

To identify the existing assets which provide a significant contribution to data capacity rates we use current network data from the Dutch Radiocommunications Agency asset register for July 2017. This contains the coordinates of all LTE cells (16,310) which operate at 800 MHz and/or 1800 MHz frequencies. Legacy 2G and 3G assets are excluded as they do not significantly contribute to data capacity. The existing 4G LTE system forms the baseline for the initial capacity calculations. We cluster all cells within 80 m into single sites (based on Annex A of [Stratix, 2015](#)), by using a buffer on all cells, and dissolving overlapping buffers, leaving an estimated 8404 sites. A point-in-polygon analysis is then undertaken to count the number of sites in 4066 postcodes. Sites need to be divided over different operators, and we work with a reasonable assumption that an operator would have access to 50% of all sites, based on their own assets complemented by (antenna) site sharing agreements. Using 4033 postcodes as the lower level statistical units for the Netherlands, results are aggregated into 725 postal code regions that share common characteristics, still providing a high degree of spatial insight, but making visualisation more efficient.

The spectrum bands considered include 700 MHz, 800 MHz, 900 MHz, 1500 MHz, 1800 MHz, 2.1 GHz, 2.6 GHz, and 3.5 GHz (3.4–3.8 GHz). We assume that in the 3.5 GHz (3.4–3.8 GHz) spectrum range, 400 MHz is available for wireless broadband applications. However, due to current restrictions this band is not available for use in the Northern part of the Netherlands due to existing (NATO) military usage. At the lower part of the band (3.4–3.6), we assume 40 MHz for the hypothetical operator with a downlink-to-uplink ratio 5:1. For the upper part (3.6–3.8 GHz) the hypothetical operator has access to 100 MHz for network densification strategies. Overall, the hypothetical operator is assumed to have a portfolio of spectrum as depicted in [Fig. 2](#).

It is assumed that only 2100 MHz and a small fraction of the 900 MHz band will continue to operate legacy technologies (2G and 3G). 800 MHz, 1800 MHz, 2600 MHz and a fraction of the 900 MHz band are assumed to be used for LTE and LTE-A systems to meet end-user demand in each scenario.

3.2. Demand module

The demand module is fed with the population data for 4033 postcodes ([Central Bureau of Statistics, 2017](#)) and divided by the surface area of each postcode (km^2) to obtain the population density ($pop_density_i$) of the i th area. A smartphone adoption rate of 79% ([Newzoo, 2018](#)) is used to estimate the total number of users ($adoption$), along with a market share parameter ($market_share$) for the hypothetical operator of 30% (where this traffic load is assumed to occur homogenously across space). Eq. (1) illustrates the demand calculation utilised:

$$Demand_{is} = \frac{\left(\left(pop_density_i \cdot \frac{adoption}{100} \right) \cdot \left(\frac{market_share}{100} \right) \right) \cdot user_speed_s}{OBF} \quad (1)$$

The $Demand_{is}$ in Mbps per km^2 is estimated on average for the i th area for each scenario (s) using the desired per-user speed ($user_speed_s$). This calculation utilises an overbooking factor (OBF) given that only a proportion of users utilise the network at a single point in time (hence, the temporal average), which is here assumed to be 50:1 ([Holma and Toskala, 2012](#)). This is based on an established demand estimation method reported in the literature by ([Oughton et al. 2018](#)).

To estimate the potential *maximum* traffic level that would trigger the need to deploy small cells, the number of *active_users_i* is first estimated for the i th area, as per Eq. (2):

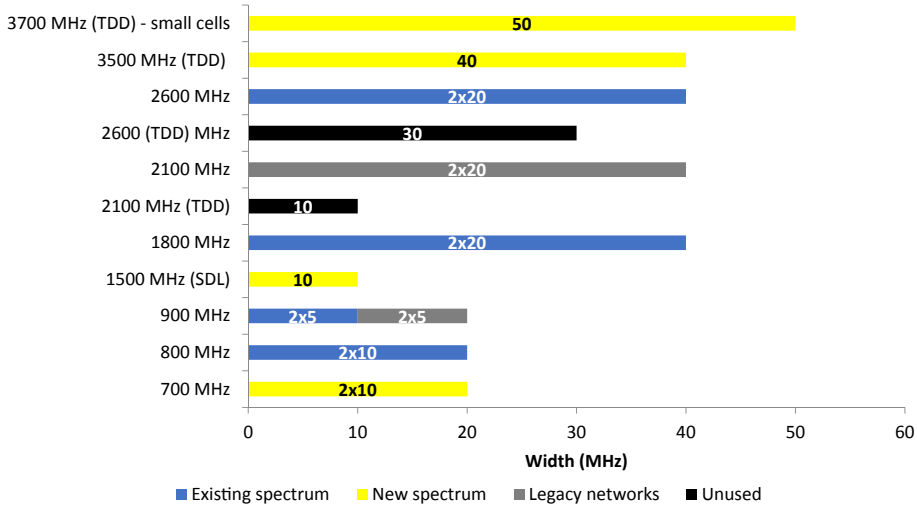


Fig. 2. Hypothetical operator spectrum portfolio.

$$active_users_i = \frac{\left(\left(pop_density_i \cdot \frac{adoption}{100} \right) \cdot \left(\frac{market_share}{100} \right) \right)}{OBF} \quad (2)$$

We aim to estimate in Eq. (3) the *maximum* average user demand ($max_user_demand_{it}$) for the i th area for a specific t technology (LTE or 5G), which can be supported across the macrocell layer (utilising the temporal *average* articulated above). This is achieved by obtaining this *maximum* supply-side capacity ($capacity_{it}$) by considering all available spectrum resources. This network capacity is estimated using the method in Section 3.5:

$$max_user_demand_{it} = \frac{capacity_{it}}{active_users_i} \quad (3)$$

Now the demand module capabilities have been articulated different infrastructure strategies can be discussed.

3.3. Infrastructure strategies

We compare three general strategies which we expect to be evaluated by operators. Firstly, a *Spectrum Integration Strategy* involves the deployment of all newly available spectrum for a hypothetical operator, including 700 MHz, 1500 MHz and 3.5 GHz, onto existing brownfield macrocellular sites (2x10 MHz@700 MHz, 10 MHz@1500 MHz and 40 MHz@3.5 GHz). Secondly, a *Small Cell Strategy* consists of the deployment of greenfield small cells operating in TDD (100 MHz@3.7 GHz). Finally, a *Hybrid Strategy* sees the integration of both previous approaches, first using all available bands from the spectrum strategy, and then the same deployment of greenfield small cells where necessary if demand is not met.

3.4. Geotypes

A ‘geotype’ is a representative settlement pattern. Areas falling into each geotype segment (urban, suburban or rural) share similar capacity-demand characteristics, leading to comparable cost characteristics for the deployment of new infrastructure. Using population density data from the demand module, postcodes statistical units are grouped based on a set of boundaries representing different percentiles of the population. Seven settlement types are used including Urban (≥ 7348 persons per km^2), Suburban 1 (≥ 4046 persons per km^2), Suburban 2 (≥ 1949 persons per km^2), Rural 1 (≥ 672 persons per km^2), Rural 2 (≥ 346 persons per km^2), Rural 3 (≥ 191 persons per km^2) and Rural 4 (≥ 0 persons per km^2), as illustrated in Fig. 3.

Geotype statistics are aggregated for total population, total area, total sites, whereas the population density and site density, is the average by geotype, as reported in Table 1. We focus on the landmass, predicated on the principle that this is the area where an operator could plausibly upgrade brownfield sites or deploy greenfield small cells. Those areas without access to 3.4–3.8 GHz in the north of the Netherlands are deemed to have limited spectrum availability. The analysis includes 16.8 million people, 8404 sites, and a landmass of 34.9 thousand km^2 . Site density is calculated using all sites and only 50% of sites. Given existing site sharing agreements, the 50% site density is used as it is assumed the hypothetical operator has this level of access.

3.5. Network dimensioning module

While the first 5G standard has been released, the standard is still evolving and maturing. We model the network performance of 5G based on the first available information from field tests (Wang et al., 2017). This section describes how the number of required

Geotype Segmentation by Postcode Area

Spectrum demarcation line identified in red

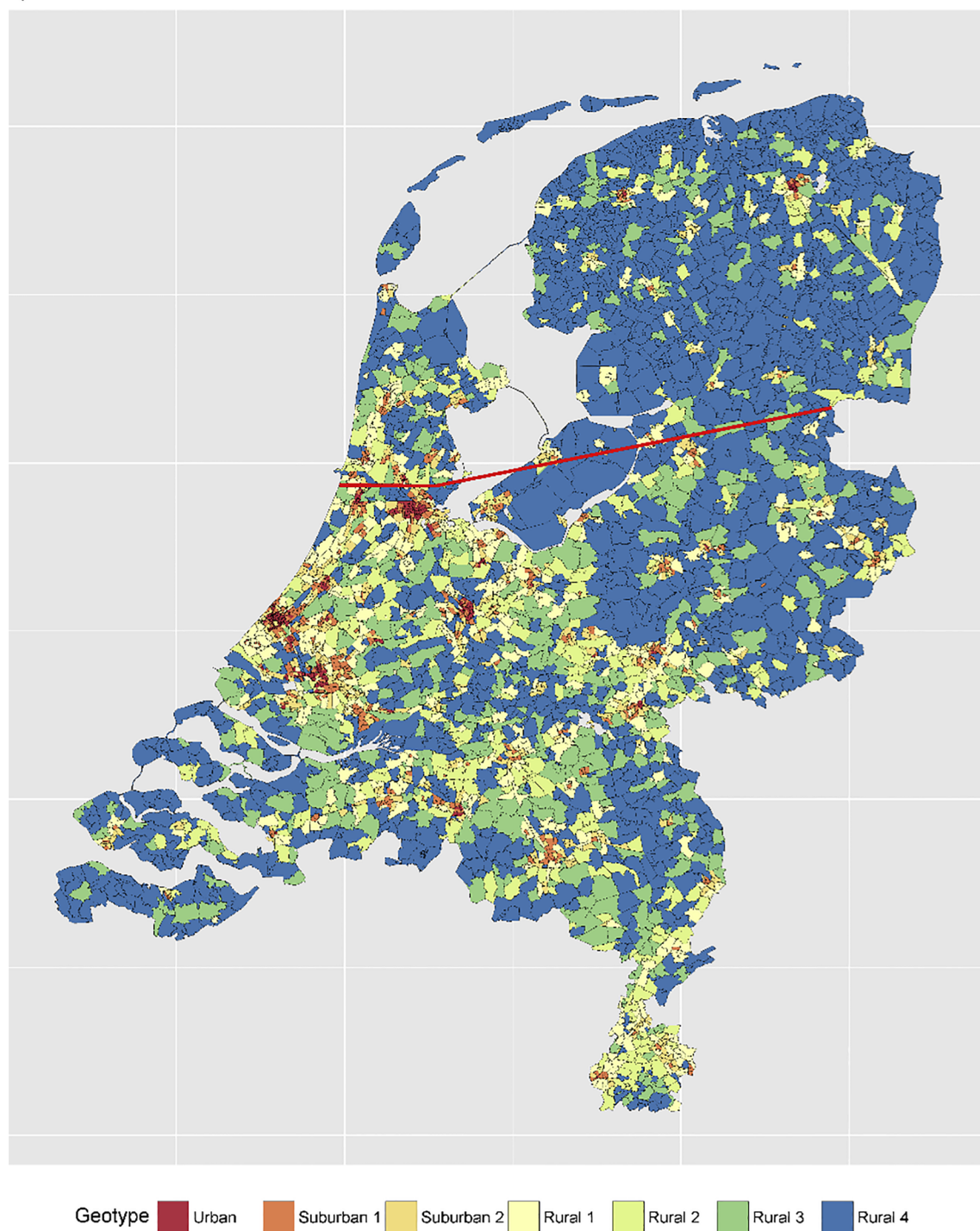


Fig. 3. Postcodes illustrated by geotype.

assets is calculated for both the macrocell and small cell networks.

Macrocell capacity is estimated based on the existing inter-site distance (ISD) derived from the base station density. For the capacity of the existing network (4G), we use system-level simulations for a typical mobile network, based on a proven methodology (Frias et al., 2017; Oughton and Frias, 2017). For each of the frequencies used in the legacy network, the methodology estimates with

Table 1
Geotype Segmentation.

Geotype	Spectrum Availability	Total Population	Total Sites	Total Area (km ²)	Average Population Density (km ²)	Average Site Density (km ²)	Average Site Density (50% site share) (km ²)
Urban	All	1,567,800	520	146	11,790	3.67	1.84
Suburban 1	All	2,896,235	1027	545	5401	1.93	0.96
Suburban 2	All	2,836,390	1075	1012	2932	1.12	0.56
Rural 1	All	2,690,045	1347	2512	1176	0.63	0.32
Rural 2	All	1,283,830	717	2657	493	0.32	0.16
Rural 3	All	1,313,645	806	4995	265	0.21	0.1
Rural 4	All	1,038,820	1368	10,857	93	0.23	0.12
Urban	Limited	115,385	34	13	9520	2.7	1.35
Suburban 1	Limited	460,025	111	90	5301	1.38	0.69
Suburban 2	Limited	509,730	194	187	2848	1.04	0.52
Rural 1	Limited	670,620	250	617	1166	0.48	0.24
Rural 2	Limited	389,720	172	824	487	0.3	0.15
Rural 3	Limited	361,045	191	1416	257	0.15	0.07
Rural 4	Limited	643,570	592	8948	68	0.07	0.04

over 90% confidence the Probability Density Function (PDF) of the signal quality (measured as the Signal to Interference and Noise Ratio, SINR) based on the propagation properties and other parameters, as described next.

This stochastic network dimensioning model utilised follows the 3GPP technical recommendations for defining transmitted power, antenna height and propagation (3GPP 2010). Using the SEAMCAT (SEAMCAT, 2010) ‘Hata Extended’ propagation model, log-normal distributions for signal loss due to (i) slow fading or shadow fading (due to clutter), and (ii) building penetration. The SEAMCAT model is valid up to 3 GHz, although it is also used for 3.5 GHz modelling and it can be expected to give reasonably reliable results for these higher frequency bands too. Other than SEAMCAT, there are no other feasible options for applying the same model across all spectrum bands to guarantee coherence across modelling results. The overbooking factor is assumed to be 1:50 in accordance with LTE network design and planning practice (Holma and Toskala, 2012).

Three clutter types are used for urban, suburban and rural geotypes. The PDF function of the SINR ($f(SINR)$) is then used to estimate the average spectral efficiency, as in Eq. (4), where the spectral efficiency at each SINR follows Mogensen et al. (2007).

$$\eta_{ISD} = \int \eta(SINR)f(SINR)dSINR \quad (4)$$

Based on the average spectral efficiency for the basestation density (η_{ISD}), the average throughput (Mbps) is calculated, as noted in Eq. (5). For this, three-sector cells are assumed and the available bandwidth at each frequency band (BW^f) is accounted for:

$$Throughput_{ISD}^{cell} = 3 \sum_f \eta_{ISD}^f BW^f \quad (5)$$

For the upgrades to 5G, we differentiate the spectrum integration strategy (when new carriers are deployed on the existing macrocells) and the small cell strategy. For the former, we assume an average spectral efficiency of 3bps/Hz based on the field tests of Wang et al. (2017) and taking into account the available spectrum. This approximately doubles the spectral efficiency of 4G systems. Regarding small cells, we assume higher spectral efficiency (6 bps/Hz) along with 50 MHz available bandwidth, a maximum coverage of 200 m and a 5:1 download-to-upload ratio.

The outputs of the network dimensioning module provide the number of basestations required, which will be used to assess necessary additional infrastructure assets and associated costs. For a detailed overview of this module see Appendix B.

3.6. Cost module

After dimensioning the different infrastructure expansion strategy options, the number of required elements per asset type is calculated for each scenario. The scenarios reflect the desired download speed per user in all geotype environments, from very urban to very rural. Cost data are then allocated to each asset type to obtain the required investment for each infrastructure strategy option. The costs used have been taken from a combination of local costs for fibre per kilometre, and asset costs from either the Ofcom Call Termination Model (MCT) (Ofcom, 2015) or the Horizon 2020 5G NORMA project (5G NORMA, 2016). The costs in the Ofcom MCT model have been broadly agreed by UK mobile operators which provides a degree of confidence as opposed to using arbitrary cost assumptions, whereas the NORMA costs are subject to more uncertainty since they are prospective estimates, but they have been agreed by the members of the consortium (including operators). As some costs are in British pounds, we have converted them into Euros based on an exchange rate of 1 Euro: 0.8955 GBP (Exchange rate as of 15th November 2017). We exclude spectrum licensing costs. Small cell deployment is assumed to take place on street furniture for a negligible (‘pepper corn’) rent. Table 2 illustrates the asset costs used.

The RAN costs include all components, such as a 5G multicarrier basestation, and as many additional carriers for each spectrum band in deployment on the macro-cell. Small cell backhaul is considered to be an OPEX, rather than a CAPEX because in many cases operators either make use of already existing connections or opt for outsourcing. Under this assumption, it would be rented from

Table 2

Deployment costs by infrastructure type.

Strategy	Spectrum integration on macrocellular network				Network densification through small cells		
Cost type	5G multicarrier BS	Additional carrier on current BS	Civil works	Fibre backhaul	Small cell equipment	Small cell civil works	Small cell backhaul
Unit	BS	Carrier	Cell site	Km	Cell site	Cell site	–
Capex (€)	45,673	16,750	20,101	22,334	2791	14,852	–

companies specialised in providing mmW connections to serve as the backhaul for 5G small cells or make use of an existing end-user connection (for instance for an office or residential building with an antenna on its rooftop).

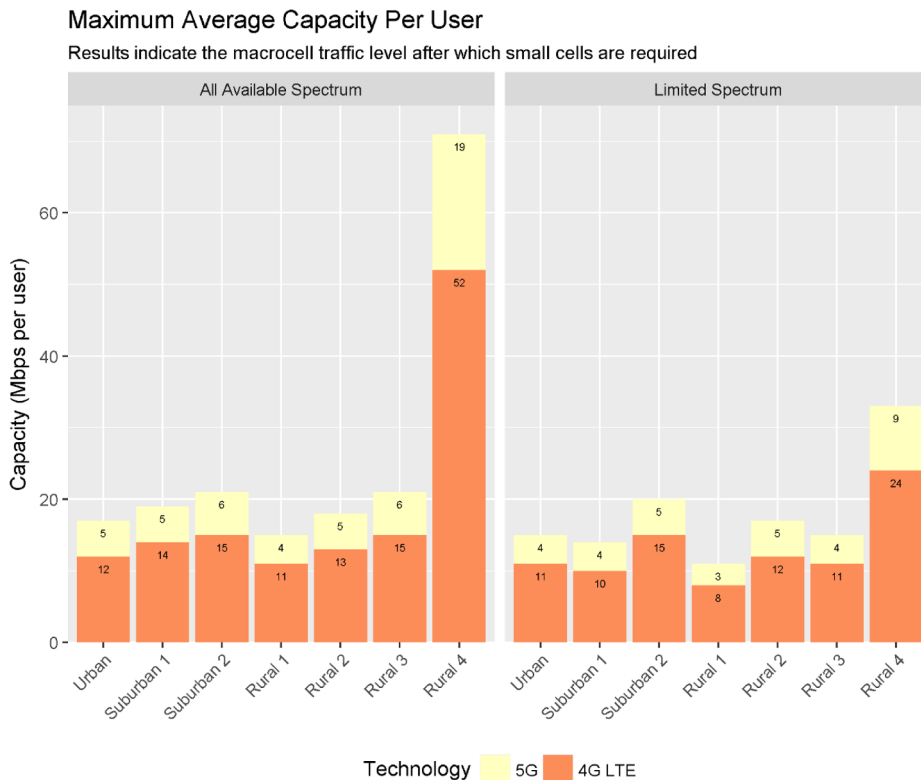
4. Results

This section details the results. To answer research question one, the first set of results quantify traffic capacity to indicate the level at which small cell deployment would be necessary. Fig. 4 illustrates the existing capacity provided by 4G LTE across numerous geotypes with different spectrum portfolios in the supply-driven approach. The metric reported represents the maximum available capacity per user, for the average temporal period, hence the *maximum average*. This ranges between 11–12 Mbps per user in urban areas, up to 24–52 Mbps per user in the most rural areas. This significant difference in performance results from rural areas having relatively low population densities, compared to urban and suburban locations.

In terms of the additional capacity 5G spectrum can provide, urban areas could see a capacity increase of 4–5 Mbps per user, compared to a more substantial 9–19 Mbps per user in lower population density areas. When these results are aggregated, the maximum average traffic capacity provided by the existing 4G LTE macrocell layer is 16 Mbps per user and the new 5G bands are capable of adding 6 Mbps per user.

We now focus on the demand-driven approach, reporting the square kilometre, aggregate, cumulative and per user cost results, as well as the interaction between supply and demand for each strategy via a capacity margin metric. Importantly, the cost results must be read in tandem with the capacity margin visualisation in Fig. 6(B), as low-cost strategies (e.g. spectrum integration) may fail to meet demand.

Overall, the costs increased as the technical specification was raised in each scenario. Hence, as Fig. 5(A) illustrates, greater

**Fig. 4.** Maximum average per user traffic level.

investment is needed per km² moving from 30 Mbps per user (Scenario 1), which is not so far from current capacity in some locations, to much more ambitious thresholds such as 100 Mbps (Scenario 2) and 300 Mbps per user (Scenario 3). Indeed, existing capacity is already close to providing 30 Mbps in less densely populated geotypes (e.g. Rural 4, where no investments would be needed). For the spectrum integration strategy, the per km² costs are very similar (equal except for Rural 4) across all scenarios (30 Mbps, 100 Mbps and 300 Mbps). This is because the strategy reaches its technological limit, hence while costs are equal across scenarios, the capacity deficit increases as it is illustrated in Fig. 6(B).

For small cells, while the per km² costs are similar across geotypes for Scenario 1, they are significantly larger in urban areas as we move to higher per-user speeds (Scenario 2 and Scenario 3). This is due to high capacity-constrained networks in these areas, which require network densification to meet intense user demand, particularly in Scenario 3. This juxtaposes Scenario 1 where the per km² costs across geotypes indicate networks are limited by coverage.

The cost structure across the different geotype segments resembles an exponential decay, with suburban areas being considerably cheaper than high population density areas. Rural area costs are very low in terms of required investments per square kilometre. However, the aggregate costs, as it will be shown later, are significantly higher.

Importantly, the use of small cells, and network densification in general becomes more important as the required speed per user increases. As the capacity margin deficit in Fig. 6(B) indicates spectrum resources are insufficient to meet demand, more small cells are therefore required. There are differences between the expansion strategies evaluated based on the breakdown of equipment costs.

In the macrocellular case, the active RAN equipment was on average 78% of the cost, with civil works being only 20% and macro backhaul 2%. In comparison, the small cell strategy had an average proportion of 84% of the capex costs being spent on civil works and only 16% on RAN equipment. As small cell backhaul is likely to be an opex cost, it is not included here. Hence, the costs for construction of the passive components comprise most of the required investment.

In terms of the aggregate costs illustrated in Fig. 5(B), the trend is generally exponential, especially in Scenario 2 and 3, with costs increasing as population density decreases. Again, Scenario 1 follows a slightly different trend as the existing network is close to providing 30 Mbps in some rural areas (e.g. Rural 4) without substantial investment. The difference in the cost, particularly between spectrum integration and small cell strategies, is notable when comparing the performance of the capacity margin in Fig. 6(B). Although expensive due to 200 m small cell radii, small cell deployments provide huge increases in capacity in areas where they can be deployed.

Fig. 6(A) illustrates cumulative cost curves by scenario and strategy indicating the required investment necessary for reaching different population coverage levels. While the costs of the spectrum integration strategy increase relatively linearly along with the population covered, the small cells rollout costs generally increase exponentially, particularly for the final 20% of the population in Scenario 2 and 3. It is also worth noting that when it comes to broad coverage and high-capacity (100 Mbps and 300 Mbps), a hybrid strategy provides little benefit. As spectrum fails to meet demand, small cells must consequently be deployed, meaning the costs end up being higher than a small cell-only strategy. Finally, Fig. 6(A) shows a general trend where the final third of the population costs almost twice the amount of the first two thirds. Indicatively, very high capacities are therefore likely to be unviable in these locations, and operators should focus on providing modest yet reliable per user speeds.

It is useful to understand the geographic distribution of the demand, the capacity and the affiliated cost. In Fig. 6(B), the capacity margin is assessed for each scenario and strategy, which indicates whether current capacity meets present demand or not. Based on this analysis, spectrum integration alone is generally unable to meet demand in all cases. But while there is only a minor capacity deficit in Scenarios 1 given the very high number of users (~5 Gbps km²), in more ambitious scenarios the deficit is much larger. For example, in other scenarios in urban areas such as Amsterdam, The Hague, Rotterdam, Utrecht and Groningen, the capacity deficit is larger than 20 Gbps per km². The use of small cells operating at 3700 MHz below the 'Amsterdam-Zwolle' spectrum demarcation line enables demand to be easily met, with a large surplus of capacity remaining in less densely populated areas.

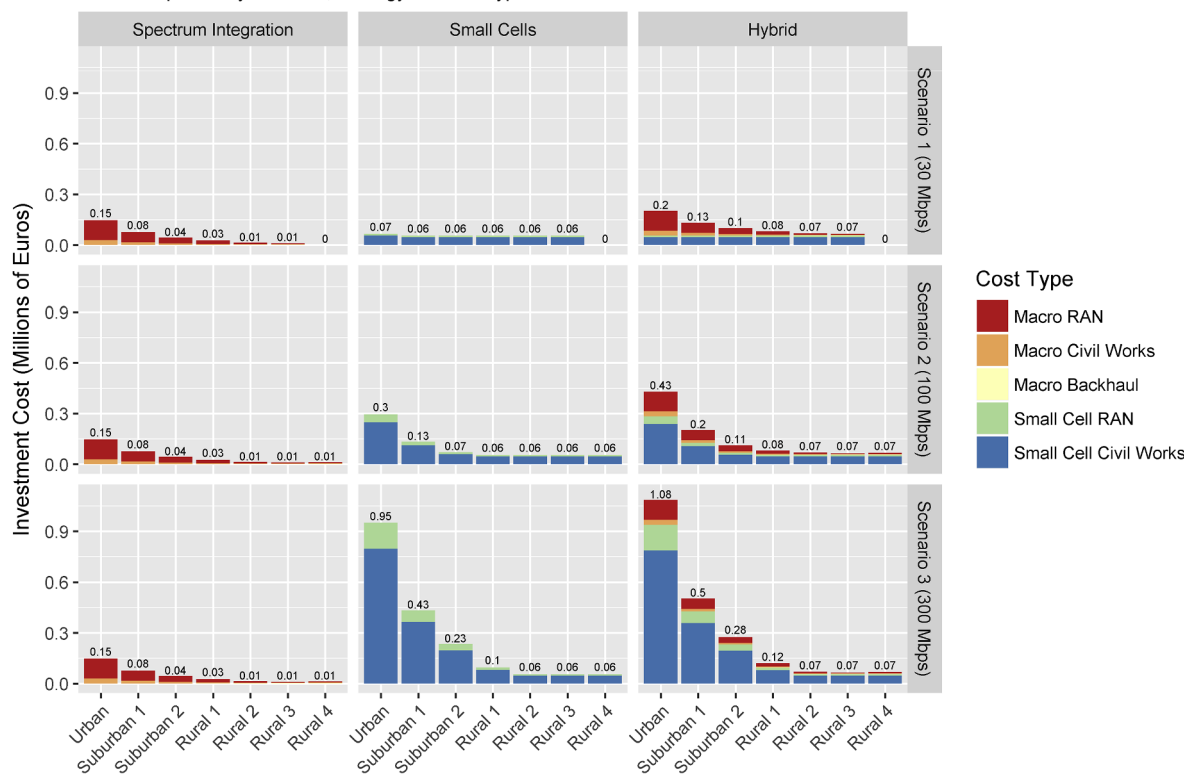
On the other hand, above this line northern areas generally end up with higher capacity margin deficits due to the fact that the 3.4–3.8 MHz band cannot be used to increase capacity via either the macrocellular network or small cells. In the model, small cells only use 3.6–3.8 GHz frequencies. Other frequency bands might also be used but this may require extensive network re-planning and still includes costs for additional cells. To provide higher capacity, a strategy deploying smaller cells is generally necessary but comes at a large cost. In this analysis, we do not assess further densification of the macrocellular network, although this may be an important development for the future.

We find that there is no capacity deficit when small cells are deployed, as illustrated in Fig. 6(B) (centre and right columns). For the cases where no small cells are deployed, such as in the spectrum integration strategy or any postcode sectors above the Amsterdam-Zwolle spectrum demarcation line, significant capacity deficits arise. Other technological solutions may be required to provide capacity in this region.

Finally, these results need to be taken one step further, and placed into the perspective of the investment cost per user, which is a good proxy for rollout feasibility. Fig. 7 reports these metrics by geotype. Most interestingly, the cost per user for Scenario 1 and 2 in urban and suburban areas, via either the small cell or hybrid strategies, is one of the most plausible investment options. For example, capex investment in small cell deployment to reach 100 Mbps per user is estimated to range between €72–85, which is a viable prospect for the hypothetical operator. This is a non-viable option however in rural geotypes due to the significantly elevated investment cost required.

A Cost Per Square Kilometer by Geotype

Results reported by scenario, strategy and cost type



B Aggregate Cost by Geotype

Results reported by scenario, strategy and cost type

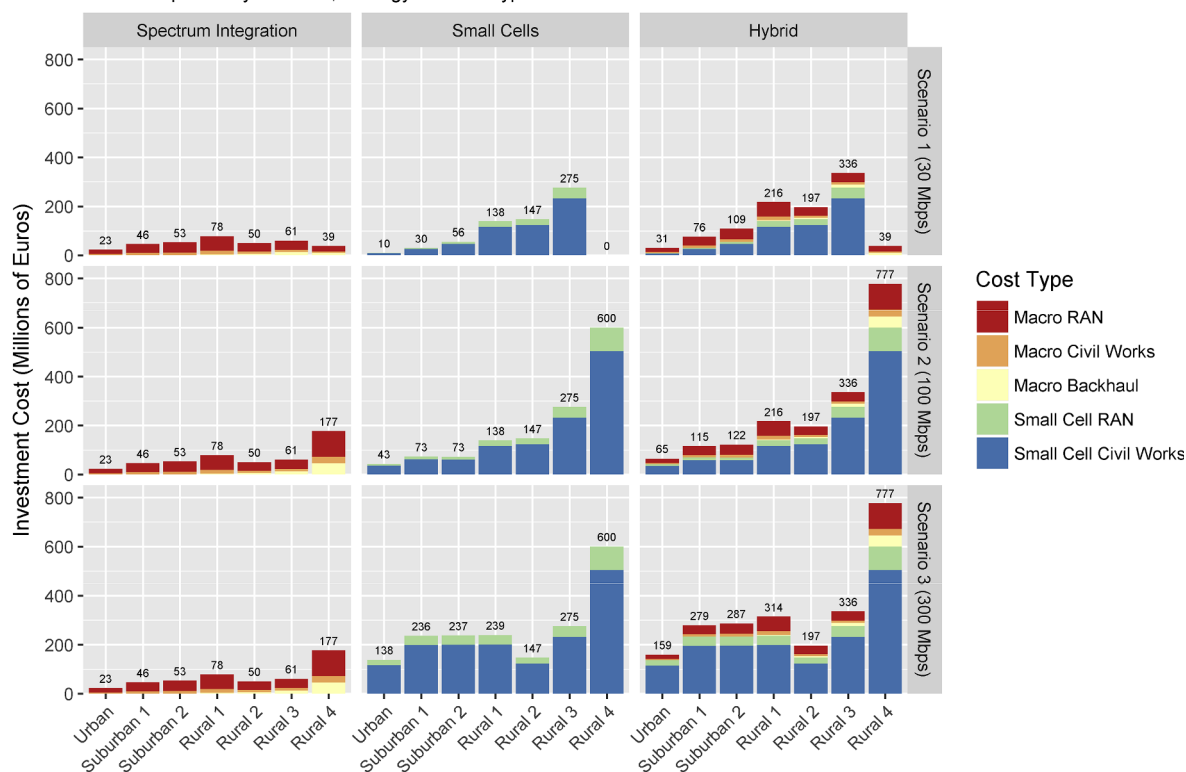
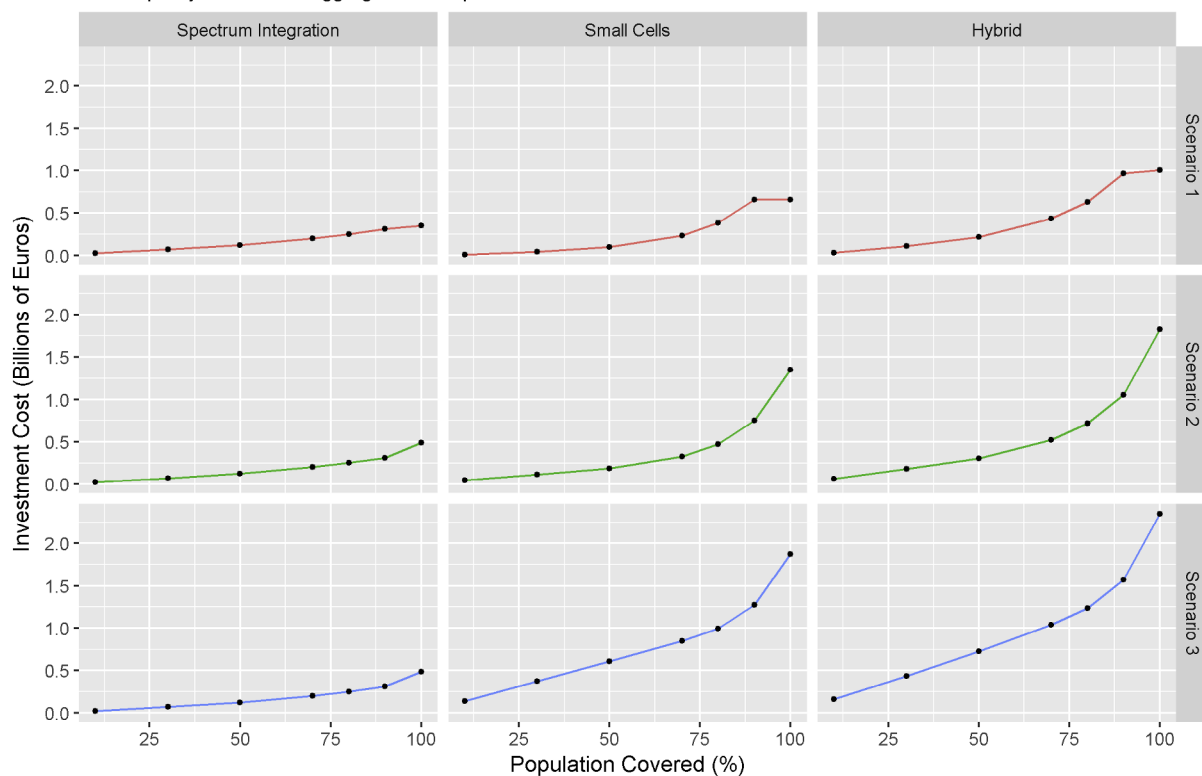


Fig. 5. (A) Deployment cost per kilometre by geotype and (B) aggregate cost by geotype.

A Cumulative Investment by Population Coverage

Cost-capacity calculations aggregated from postcodes



B Capacity Margin by Scenario

Capacity Margin per municipality aggregated from postcodes

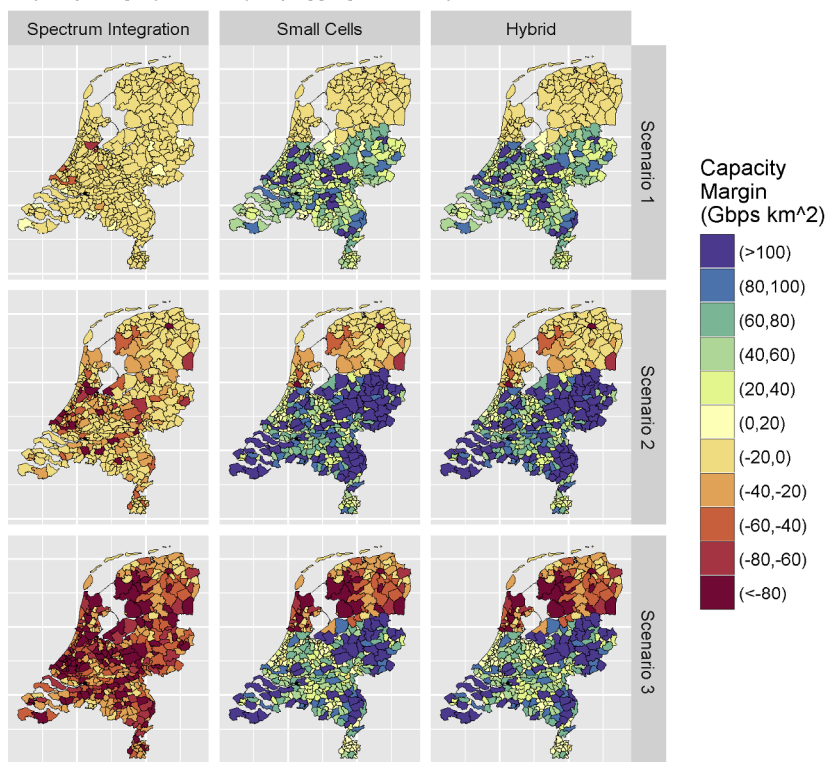


Fig. 6. (A) Cumulative investment cost and (B) capacity margin by municipality.

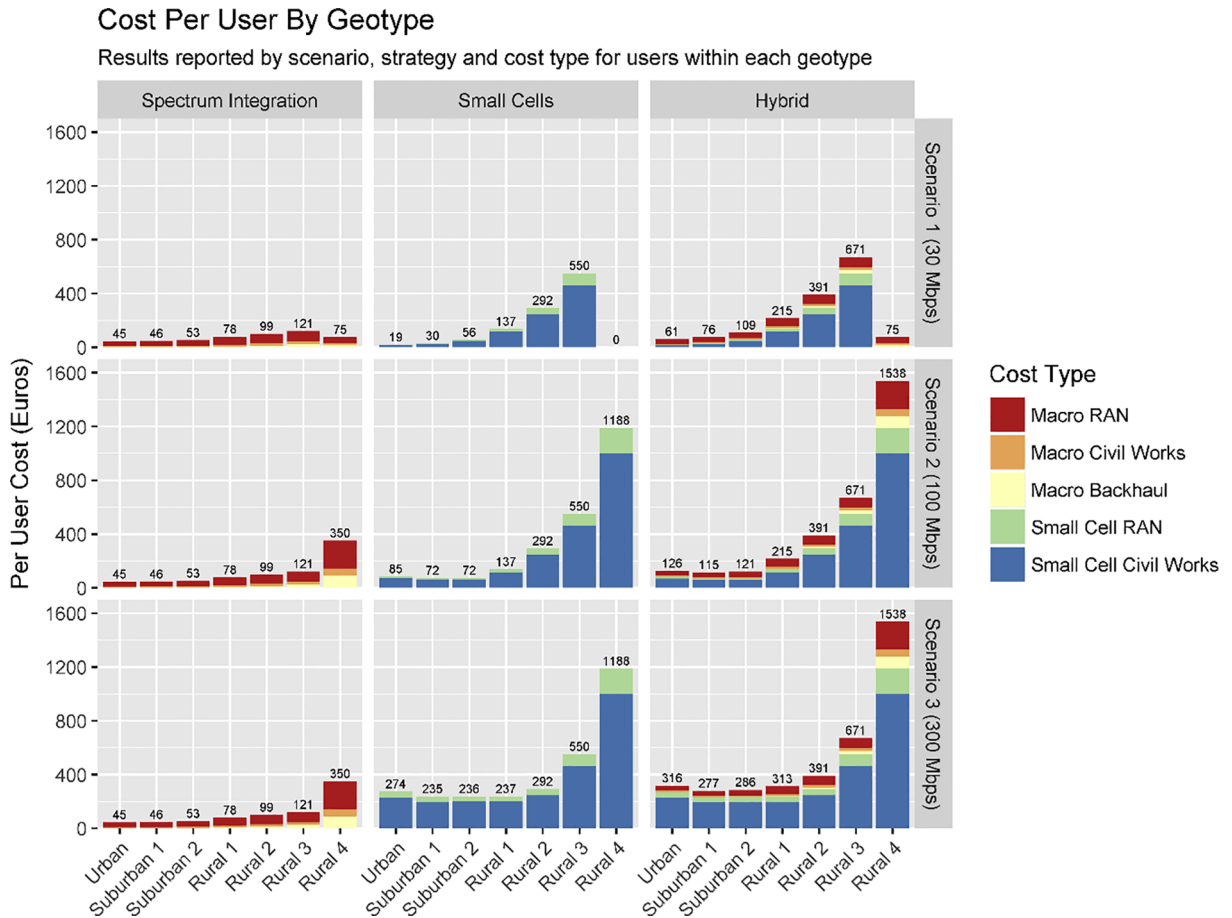


Fig. 7. Cost per user by geotype.

5. Discussion

Having reported the results, we now evaluate and discuss the findings.

5.1. What is the potential traffic level that would trigger the need to deploy small cells?

The new per user capacity provided by the 700 MHz, 1500 MHz and 3.5 GHz bands provide an approximate improvement of 40%, based on the hypothetical operator modelled in this analysis. The existing 4G LTE macrocell layer can support a maximum average of 16 Mbps per user, with the new 5G spectrum bands providing an additional capacity of 6 Mbps per user. This is a critical threshold for the economics of 5G, because reutilising the existing macrocell layer allows affordable capacity expansion and efficient rollout. Above this threshold, the economics of delivering new capacity becomes considerably more expensive because network densification is required.

5.2. For different expansion strategies what are the key cost components?

The analysis quantified the main cost components distinguished by strategy type. We found that in the spectrum integration strategy approximately 78% of the cost per km² was attributed to macrocellular RAN equipment upgrades, 20% associated with civil works and 2% backhaul upgrades. The aggregate cost structure for the Netherlands was similar for the RAN, civil works and backhaul, being 70%, 18% and 12% respectively. In the small cell strategy, only 16% of the small cell deployment cost resulted from the small cell RAN assets, whereas civil works accounted for 84% of the cost, suggesting passive infrastructure sharing between competitors could be beneficial for all. Importantly, as 5G small cell backhaul is an opex, the small cell component structure was similar between the per km² and aggregate cost. Given the expected density of 5G networks, it is very likely that at least the backhaul

of the small cells will be shared or indeed outsourced to other companies, specialised in providing fibre or mmWave connections to serve as the backhaul for 5G small cells. An important caveat is that spectrum acquisition costs were excluded from the analysis. Further developments need to integrate opex costs into the analysis to provide a new layer of information.

5.3. What is the cumulative cost of covering different proportions of the population?

The cumulative cost of covering different proportions of the population was quantified by the analysis, showing the required investment in meeting different coverage levels, based on desired end-user speed. The seven geotypes used across urban, suburban and rural areas coincided with the 30th, 50th, 70th, 80th, 90th percentile boundaries. We find that when averaging across each scenario and strategy the urban population (the first 30% of the most densely populated areas) only accounted for 5% of the required investment cost. Subsequently, the suburban population (the next 40% of the most densely populated areas) only constituted 20% of the required investment. Therefore, the final 30% constituted approximately 75% of the infrastructure cost, three quarters of the required investment on average across all scenarios and strategies, emphasising the exponential nature of rolling out telecommunications coverage to low density, rural areas. Further development of this system could apply optimisation methods to investment decision making, based on delivering different capacity levels to different proportions of the population (e.g. 300 Mbps urban, 100 Mbps suburban and 30 Mbps rural).

5.4. How do different strategies perform in meeting demand?

The results achieved can help decision makers understand the performance of different strategies. Spectrum integration strategies performed the poorest in meeting the ambitious per user speeds set in scenarios 1–3. On average, the capacity margin for each postcode ranged from -0.4 Gbps per km^2 for 30 Mbps in Scenario 1, up to deficit of -7.3 Gbps per km^2 for 300 Mbps in Scenario 3. This contrasted with small cell deployments which ranged from a capacity margin surplus of 3.1 Gbps per km^2 in Scenario 1, down to 2.6 Gbps per km^2 in Scenario 3. The hybrid strategy saw little difference, with a capacity surplus ranging from 3.2 Gbps per km^2 in Scenario 1, down again to 2.6 Gbps per km^2 in Scenario 3. These results therefore show that based on the technological characteristics extrapolated here from 4G LTE and 4G Advanced, very high per user speeds cannot be easily achieved based on the sub-5 GHz spectrum being made available through 5G. Massive MIMO applications utilising 3.5 GHz may well provide increased spectral efficiency on these figures, but it is unlikely to enable improvements which can meet the ambitious per user targets evaluated here. Additionally, millimetre wave spectrum (26 GHz in Europe) may also provide new bandwidth that can be utilised, but propagation can be challenging and is yet to be commercially deployed. Finally, the hybrid strategy indicated that if the desired per user rate is beyond the capacity provided by spectrum, therefore requiring small cell deployment, spectrum integration provides little additional benefit. Therefore, MNOs can use these results to optimise available capital expenditure by choosing to deploy either occasional small cell ‘hot-spots’ with macrocellular wide-area coverage (e.g. suburban train station), or complete blanket coverage with small cells (dense urban centre). Importantly, the decision to continue operating a macrocellular network alongside blanket small cell coverage, potentially provides only marginal additional value to users, especially given the analysis undertaken by (Webb, 2017).

5.5. What are the investment costs per user?

The key output from the analysis related to the per user cost in each geotype which can be linked to the monthly subscriptions fees MNOs have from their own customer base. This is essential information for decision making when assessing the viability of different investments. In Scenario 1, per user average costs ranged between €19–61 in urban areas, €43–92 in suburban areas and €93–338 in rural areas. The lower end of these investment costs are viable, particularly for urban and suburban areas. One reason they are so low is because of the existing high-capacity network in the Netherlands, but given 30 Mbps is already common place consumers will expect a new, more ambitious level of service. In Scenario 2, costs were still promising for urban (€45–126) and suburban areas (€49–118), whereas rural areas begin to become less feasible (€162–704). Finally, in Scenario 3 per user costs ranged from €45–316 in urban areas, €49–281 in suburban areas, all the way up to €162–728 in rural areas. Further development of this analysis should address expected revenue benefits and juxtapose these against required investment costs using a cost-benefit ratio.

5.6. Methodological comments

Several simplifications had to be made to undertake the analysis reported here which merit further discussion.

Firstly, mapping basestations to postcodes is a necessary simplification, however this could introduce uncertainty into the results. For example, the use of artificial spatial boundaries at the local level assume users do not access cells outside their postcode area, which may take place, hence reducing the accuracy of the calculations by under-estimating capacity. A trade-off exists when trying to address this issue, as spatially granular units capture local heterogeneity well at the expense of assuming no inter-postcode cellular access.

Secondly, a key assumption utilised in the analysis was the relationship between market share and generated traffic. In this case, if

an operator has 30% market share it does not necessarily mean it will carry 30% of aggregate traffic, but the analysis focused on utilising the notion of a ‘hypothetical operator’, necessitating certain modelling simplifications. The future development of this research includes an interactive web-based tool which allows non-technical users to run the model, altering key parameters such as this, via a graphical user interface.

Thirdly, the re-farming of existing spectrum bands was not considered in this analysis but could be a useful way to expand future data capacity. For example, the discussion around switching off 2G/3G could see bands such as 900 MHz re-farmed to enable greater spectral efficiency improvements, for example by using 5G. As we do not consider millimetre wave in this analysis, this spectrum could be an additional source of capacity once deployed. Additionally, one area of uncertainty is the 5G spectral efficiency values (3–6 bps/Hz) which came from a single source. Therefore, with new measurement results likely to be released from 5G testbeds in coming years, as 5G technologies begin to mature, further analysis could be carried out to update the estimated results.

6. Conclusions

In this paper an analysis was undertaken which quantified the capacity, coverage and cost of different 5G infrastructure strategies. The purpose of this activity was to address the lack of existing strategic analysis of 5G, particularly for the main use case of Enhanced Mobile Broadband (eMBB). Indeed, MNOs, governments and other digital ecosystem actors, need to understand the investment costs involved in different levels of capacity and coverage.

The supply-driven analysis finds an improvement of 40% is enabled by utilising a spectrum integration strategy for capacity expansion (700 MHz, 1500 MHz and 3.5 GHz), based on the hypothetical operator modelled in this analysis. In total, when combined with 4G LTE, a 5G network utilising existing macrocells can enable a maximum average per user capacity of 24 Mbps at the cell edge. After this point, network densification via small cell deployment is required, which can provide significant capacity enhancement but at a substantial cost.

The demand-driven analysis reiterates that an average speed of 30 Mbps per user cannot be delivered everywhere and at all times by purely integrating new 5G spectrum into the existing macrocellular network. However, this strategy would only cost 750 million Euros, which would likely be the preferred option for most operators, when compared to the cost of mass small cell deployment targeted at higher capacities. Importantly, targeted small cell deployments can be delivered in the densest urban areas to provide superior per user capacity for high traffic demand applications such as virtual or augmented reality. This approach is supported when considering the general costs of delivery, whereby covering the urban population in the first 30% of the most densely populated areas accounted for only 5% (on average) of the total cost. Suburban populations in the next 40% of the most densely populated areas constituted 20% of the required investment. Therefore, the final 30% of the population in rural areas, on average comprised 75% of the deployment cost. In conclusion, we find that always delivering an average data rate per user of either 100 or 300Mbps everywhere is very difficult to achieve based on the capacity-expansion strategies compared, motivating the need for targeted small cells.

We reiterate the point that many of the technological solutions we are hoping will solve the challenges being faced in society (and the global economy), depend on sufficient capacity and coverage of wireless communications (e.g. the Internet of Things, Smart Cities, Smart Healthcare, Smart Infrastructure etc.). Therefore, we cannot afford to undertake poor decision making when it comes to digital infrastructure, as getting the right amount of capacity and coverage to those locations that require certain services, in a cost-efficient way for consumers, is essential. Given the wealth of new data sources that have arisen in recent years, further analysis should integrate these sources, both in terms of received coverage per user and revenue generation per cell site.

Declarations of interest

None

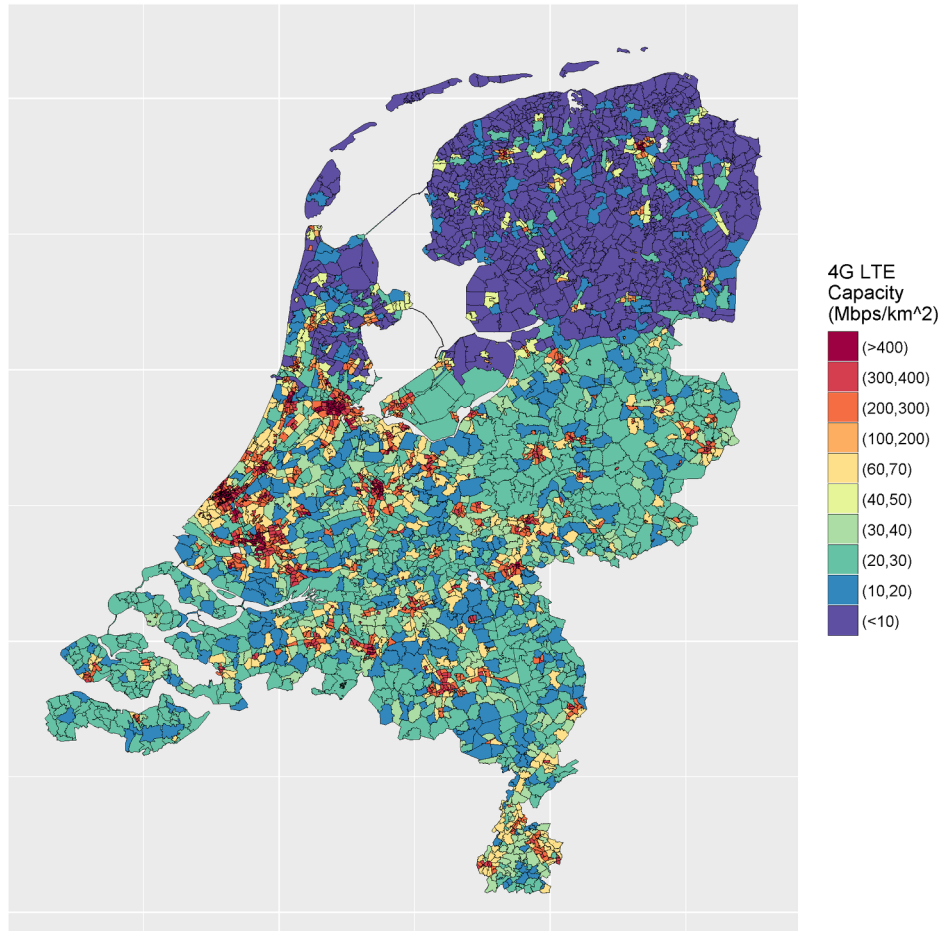
Acknowledgements

Edward Oughton would like to express his gratitude to the UK Engineering and Physical Science Research Council for funding via grant EP/N017064/1: Multi-scale InfraSTRUCTure systems AnaLytics (Mistral). This report describes the results of a research project commissioned by the Dutch Ministry of Economic Affairs and Climate Policy. We would like to thank all participants of a workshop held to evaluate the research presented in this paper, in The Hague on 20th November 2017. We would also like to thank Hind Abdulaziz, Henny Xu, Raymond Bouwman, Kees Mulder and Maarten van Waveren for feedback and direction. The authors have no competing interests.

Appendix A. Existing 4G LTE capacity reported by postcode

Existing 4G LTE Capacity

Estimates reported for 725 postal code regions



Appendix B. Network dimensioning module

This appendix provides a detailed explanation of the network dimensioning process utilised to estimate wireless network capacity. This begins with estimating the existing 4G LTE capacity. The macrocell network performance uses the method illustrated in Fig. B1.

To estimate macrocell capacity the current site density is calculated based on the existing inter-site distance (ISD) derived from the base station density, calculated using the basestation locations shown in Fig. B2.

To identify the existing assets which provide a significant contribution to data capacity rates we use current network data from the Dutch Radiocommunications Agency asset register for July 2017. This contains the coordinates of all LTE cells (16,310) which operate at 800 MHz and/or 1800 MHz frequencies. Legacy 2G and 3G assets are excluded as they do not significantly contribute to data capacity. The existing capacity of the 4G LTE system forms the baseline for the initial capacity calculations. We cluster all cells within 80 m into single sites (based on Annex A of Stratix, 2015), by using a buffer on all cells, and dissolving overlapping buffers, leaving an estimated 8404 sites (Fig. B3). A point-in-polygon analysis is then undertaken to count the number of sites in 4066 postcodes. Sites need to be divided over different operators, and we work with a reasonable assumption that an operator would have access to 50% of all sites, based on their own assets complemented by (antenna) site sharing agreements. Using 4033 postcodes as the lower level statistical units for the Netherlands, results are aggregated into 725 postal code regions that share common characteristics, still providing a high degree of spatial insight, but making visualisation more efficient.

Based on this basestation density, the model uses system-level simulations of a typical mobile network to estimate the current network capacity, which depends on the propagation properties of the existing 4G bands. In the case under study, we assume 4G networks have been deployed using the 800 MHz, 900 MHz, 1800 MHz and 2600 MHz bands.

For each of these frequency bands, we estimate the spatial probability distribution of the quality of the received signal (measured

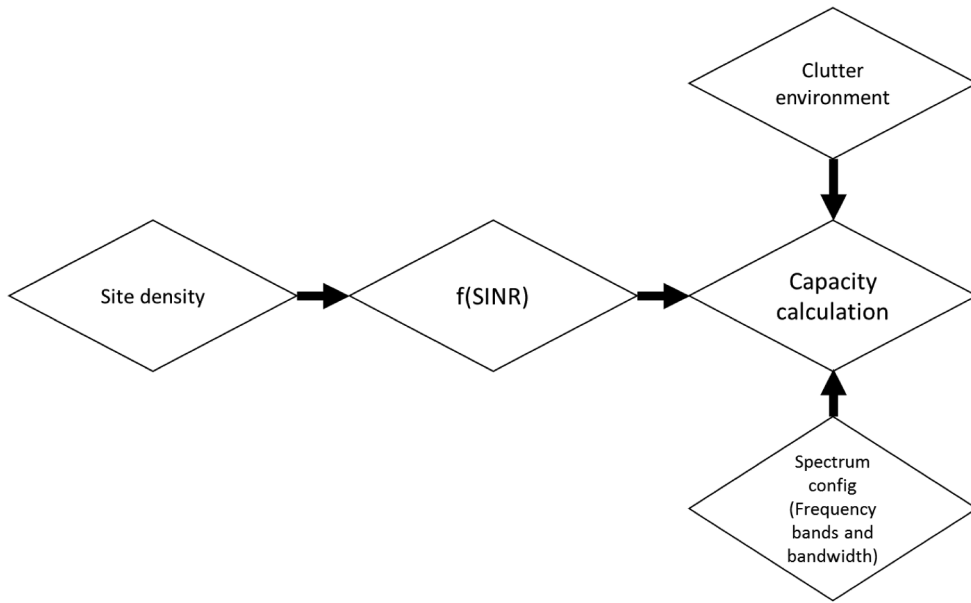


Fig. B1. Asset calculations for macrocell and small cell configurations.



Fig. B2. Base station location map used to derive the Inter-Site Distance.

as the Signal to Interference and Noise Ratio, SINR) based on the propagation properties and other parameters specified. The calculation of the SINR distribution is carried out through a Monte Carlo simulation reflecting all the variables that affect quality of the received signal including propagation losses (due to the physical distance between transmitter and receiver), shadow fading (due to large obstacles) and building penetration losses. While propagation losses may be modelled deterministically using a Hata-Extended propagation model (SEAMCAT, 2010), shadow fading and building penetration must be modelled through log-normal distributions. For transmitted power and network parameters we specifically follow the 3GPP technical recommendations (3GPP 2010). Three clutter types are used for urban, suburban and rural geotypes. Table B1 shows the values assumed for the each of the phenomena considered in the stochastic model. For further details of the methodology, the reader is referred to (Frias, González-Valderrama, and Pérez Martínez 2017).

To estimate the Probability Density Function (PDF) of the signal quality, the simulations are run until the estimation reaches 90% confidence the received signal quality.

The average spectral efficiency for each frequency band at each ISD is then estimated using the PDF function of the SINR

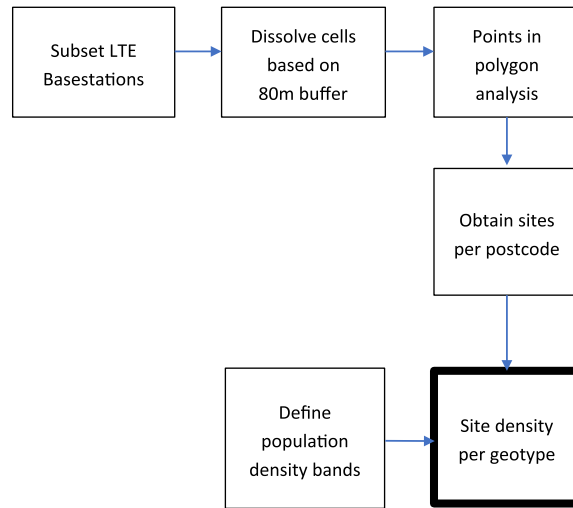


Fig. B3. Statistical distribution estimation for received Signal to Interference and Noise Ratio (SINR).

Table B1

Key network dimensioning parameters.

Parameter	Value
Network architecture	Macrocell RAN architecture
Propagation losses	Frequency reuse factor Model
Shadow fading	% indoor users Antenna height and transmitted power log-normal distribution
Building penetration loss	log-normal distribution
	Three-sector cells
	1
	SEAMCAT (2010) ¹
	50% urban and suburban, 0% rural (3GPP 2010)
	$\mu = 0$
	$\sigma = \begin{cases} 4.2 + 1.3\log_{10}(f(\text{MHz}))\text{dB}; & \text{urban} \\ 3.5 + 1.3\log_{10}(f(\text{MHz}))\text{dB}; & \text{other} \end{cases}$
	$(\mu, \sigma) = (12 \text{ dB}, 6.5 \text{ dB})$

¹ The SEAMCAT model is valid up to 3 GHz, although it is also used for 3.5 GHz modelling and it can be expected to give reasonably reliable results for these higher frequency bands also. Other than SEAMCAT, there are no other feasible options for applying the same model across all spectrum bands to guarantee coherence across modelling results.

($f(\text{SINR})$), as in Eq. B(1), where $\eta(\text{SINR})$ is the spectral efficiency at each SINR for LTE technologies (Mogensen et al, 2007).

$$\eta_{\text{ISD}} = \int \eta(\text{SINR})f(\text{SINR})d\text{SINR} \quad (\text{B1})$$

Based on the average spectral efficiency for the basestation density (η_{ISD}^f) and frequency band, the average throughput (Mbps) is calculated to estimate capacity, as noted in Eq. B(2). For this, three-sector cells are assumed and the available bandwidth at each frequency band (BW^f) is accounted for:

$$\text{Existing capacity}_{\text{ISD}}^{\text{cell}} = 3 \sum_f \eta_{\text{ISD}}^f BW^f \quad (\text{B2})$$

For integrating new spectrum on existing macrocells the following method is then utilised. We assume an average spectral efficiency of 3bps/Hz based on the field tests of (Wang et al., 2017) and taking into account the available. This is approximately double the spectral efficiency of 4G systems. We do not differentiate across spectrum bands, since we assume the higher propagation losses in high frequencies will be compensated by beamforming techniques. The additional capacity provide by this upgrade to 5G is defined in Eq. B(3):

$$\text{Additional capacity}_{\text{spectrum strategy}}^{\text{cell}} = 3 \sum_f \gamma BW^f \quad (\text{B3})$$

where γ is the average spectral efficiency in 5G (3 bps/Hz) and BW^f is the bandwidth available at each new frequency band, i.e. 40 MHz at 3500 MHz, 10 MHz at 1500 MHz, and 2×10 MHz at 700 MHz.

The small cells rollout strategy option involves deploying these assets in the 3.7 GHz range (3.6 to 3.8 GHz) using TDD mode. To estimate the required number of small cells, high spectral efficiency is assumed (6 bps/Hz) along with 50 MHz available bandwidth, a maximum coverage of 200 m and a 5:1 download-to-upload ratio, utilising Eq. B(4):

$$\text{Additional capacity}_{\text{small cells strategy}}^{\text{cell}} = \alpha \gamma BW \quad (\text{B4})$$

where α is the download-to-upload ration (4/5), γ is the average spectral efficiency in 5G at short distances (6 bps/Hz) and BW is the bandwidth available at 3700 MHz (50 MHz).

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