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The potential of small cell deployment in theory and practice

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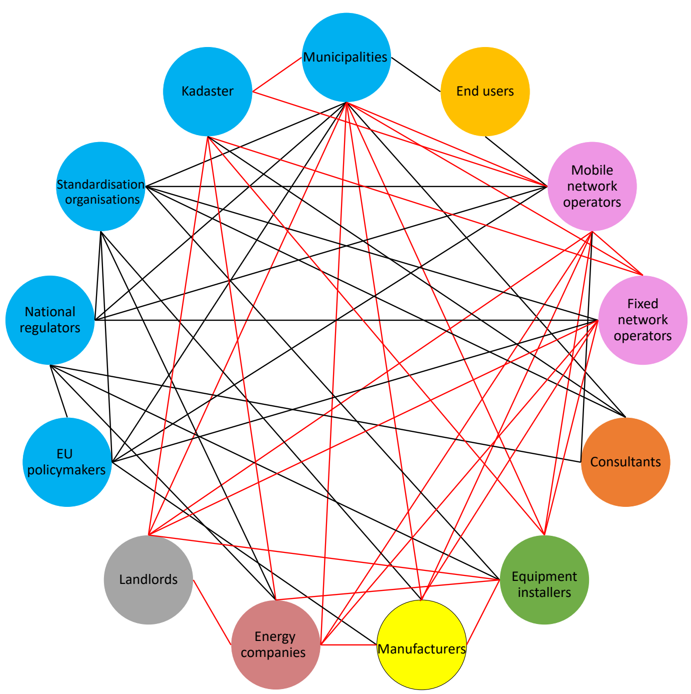

Abstract

As digital communication networks become integral to society and the economy—driving everything from personal communication to business operations and smart city infrastructure—the capacity of these networks must continuously expand to accommodate higher data volumes. The Ericsson Mobility Report demonstrates the growing need for higher throughput and increased network capacity to meet end-user expectations. One of the viable approaches to increase network capacity is through the deployment of small cells.

In general, the related axioma is: the higher the offered bandwidth (higher radio frequencies), the shorter the radio ranges will be. Small cells provide additional capacity (preferably) by means of high-frequency bands such as 3.5 GHz and 26 GHz offloading the macro network in particular short-range hotspots. Small cells can deliver higher data rates to end users, making their deployment essential at hotspots in densely populated urban areas where additional capacity will be required. This master's thesis evaluates Radio Access Network (RAN) architecture options for combining macro cells and small cells from both theoretical and practical perspectives.

The main finding from the Radio Access Network-related theoretical analysis is that the RAN architecture split option 7.2x recommended by the O-RAN Alliance is the optimal solution for indoor and outdoor deployment of small cells. Split option 7.2x offers significant benefits, such as minimising the impact on transport bandwidth while enhancing the virtualisation capabilities of the gNB Central Unit (CU) and Distributed Unit (DU), and enabling a cost-effective design of the Radio Unit (RU).

To gain an understanding of the practicalities involved in small cell deployment, this master thesis, through the Utrecht practical case study, examines potential locations for the installation of RUs, DUs, and CUs using a combination of expert interviews, Google Street View analysis, QGIS visualisations, and site visits. Proposed locations for RUs include three tall lamp posts and two security camera poles, while wharf cellars managed by Stedin and a macro cell base station are recommended for the installation of CUs and DUs. These recommendations are based on an analysis of power availability, transport, site accessibility and expert interviews. From the research it is concluded that small cell deployment in the Utrecht researched area is feasible, provided that specific challenging boundary conditions are met such as collaboration among MNOs and the use of existing poles.

The practical part of this thesis research also delves into the complex interplay of eight socioeconomic sectors and their roles in small cell deployment, providing insights into the trans-sector nature of this project. The main results from this practical part of the research concern the conclusions from the Utrecht practical case study about realizing small cells:

1. The rollout of small cells is a complex multi-actor value case with substantially more actors to collaborate in comparison with rolling out macro cells by primarily telecom operators and municipalities (issuing licenses).

2. Municipalities are best suited to fulfil the role of orchestrator in the rollout of small cells because they can coordinate diverse stakeholders to ensure seamless integration with existing infrastructure, maintain city aesthetics and establish a direct line of communication with residents for feedback and service improvement.

Based on some representative calculations of small cell deployments in the city of Utrecht we obtained good insight into the complexity as well as cost of small cells. A few of the quantitative results are mentioned below: [1]

- The price of a small cell is roughly around €60,000 per small cell site, including digging for transmission and power costs.

- In case the fronthaul is replaced by a wireless connection, roughly 30% of cost saving can be achieved.

[1]Please note that quantitative values mentioned below have been obtained based on very specific assumptions in a very specific use case location. However, we believe the values can roughly be assumed for other use cases.

Acknowledgements

I would like to extend my deepest gratitude to everyone who contributed to the completion of this thesis.

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Contents

Chapter 1

Introduction

1.1 Problem statement and research gap

Digital communication networks have become a vital component of modern society and the economy, underpinning everything from personal communication and business operations to smart city infrastructure and emerging technologies [21]. As reliance on these networks grows, so does the demand for higher data volumes. According to the Ericsson Mobility Report from November 2015, the average data usage per smartphone was 2 GB per month. By 2019, this figure had surged to 10 GB per month, and it is projected to reach 35 GB per month by 2025 and 42 GB by 2029 [7]. This rapid increase in data usage demonstrates a critical need for higher throughput and expanded network capacity to meet end-user expectations and sustain economic and social activities. To address this growing demand, mobile operators are exploring various strategies to enhance network capacity. One of the most viable approaches is the deployment of small cells, which complement existing macrocell networks by providing additional capacity in high-demand areas [3]. Small cells operate at higher radio frequencies, such as 3.5 GHz and 26 GHz, which offer greater bandwidth and are limited in range. This makes them particularly effective for offloading data traffic from the macro network in short-range hotspots within densely populated urban areas, where additional capacity is critically needed. Given their ability to deliver higher data rates to end users, small cells are becoming increasingly essential for enhancing network performance in areas where demand for data services is high. As a result, the integration of small cells within existing infrastructure is anticipated to play a crucial role in ensuring seamless network performance in future 5G networks.

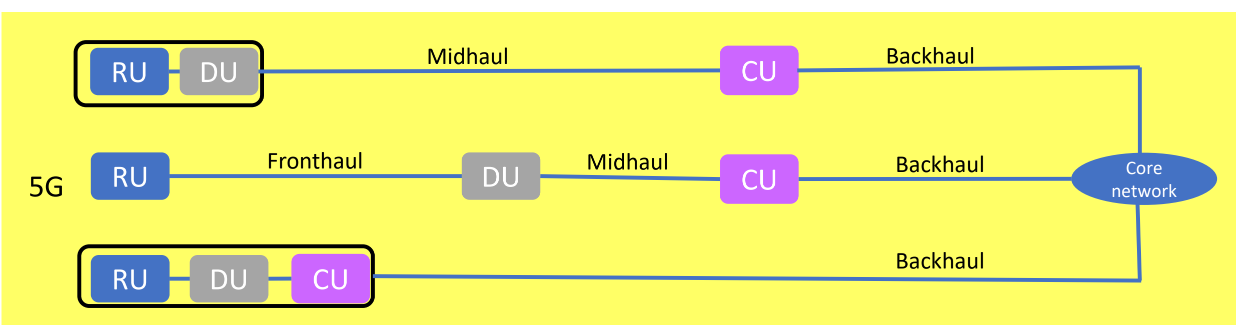

Figure 1: Three potential collocation configurations of RU, DU and CU

How to efficiently integrate 5G small cells into existing infrastructure, particularly in terms of topology and architecture involving combinations of Radio Units (RU), Distributed Units (DU) and Central Units (CU), while creating minimal impact in its surroundings is a problem that has not yet been fully explored. This master thesis aims to address this gap by assessing the most effective combinations (shown in figure 1) of these architectural elements in the combination of small cells and macro cells into the existing telecom and built infrastructure while maintaining city aesthetics and optimising costs. With the continuous need for increased capacity and network coverage, the deployment of small cells seems like a critical next step for mobile network operators. Some of the practical challenges small cell deployment currently faces include:

- Fragmentation or lack of scalability, impacting total cost of ownership.
- Limited cooperation and risk/reward sharing among stakeholders, including enterprises, cities, spectrum owners, and digital services providers.
- Challenges related to the impact on macro networks, power and data backhaul, and site acquisition.

To address these practical aspects for the deployment of small cells, the research examines business modelling intricacies, including the role of neutral hosts as intermediaries between building owners and mobile network operators, and assesses the viability and impact of cooperation with neutral hosts in small cell deployment. Currently, the Municipality of Utrecht is confronted with its own set of challenges in orchestrating and facilitating a small cell network for the city's residents. Key issues include the absence of specific regulations for small cell placement, limited control over the actions of mobile network operators and energy companies, and the lack of forecasts regarding future traffic volumes and power needs. Additionally, protecting historic sites and minimizing disruptions to public spaces, particularly in areas with ancient wharf cellars, complicate the installation of new underground cabling and power cabinets.

In this Utrecht practical case study, the feasibility of small cell deployment is investigated by taking into account, o.a., the transport network of KPN, the power grid, underground infrastructure, available space above and under the ground, and the municipality rules and requirements.

1.2 Research objective

The objective of this master thesis research is to identify the optimal configuration of 5G small cells by considering the practicalities. The research focuses on determining the optimal locations for Radio Units (RU), Distributed Units (DU), and Central Units (CU) in the context of the Utrecht practical case study, taking into account the transport network, power grid, municipality rules, requirements and cost estimations. This also involves exploring which 5G RAN architecture split options are most suitable for specific environments and use cases. Additionally, the study investigates the various sectors and actors involved in the deployment of small cells, examining their roles within the practical framework of the Dutch telecom market. Furthermore, the thesis looks into the necessary rules and regulations for the seamless integration of small cells within the existing telecommunications ecosystem.

This thesis also explores the potential role of neutral hosts in indoor solutions, facilitated through cooperation among telecom operators, building owners, municipalities, manufacturers, and other stakeholders. Furthermore, this thesis includes an analysis of the current situation in the Netherlands telecom market, focusing on cooperation forms and infrastructure sharing.

1.3 Research questions

The goal of this master thesis is to contribute to the understanding of the effective combinations of the architectural elements of small cells in combination with the macro cells as well as analyse the practicalities involved in the integration of small cells in the built infrastructure. In order to address each of these goals, three research questions have been identified in this master thesis project. RQ1 and RQ2 are partially theoretical and RQ3 is based on the Utrecht practical case study:

1. RQ1: Which is the optimal configuration for deployment of small cells from the perspective of cost, flexibility, customer satisfaction, and practicality point of view?
2. RQ2: Regarding 5G small cell deployment, which option of split 5G RAN architecture are optimal for which specific environment and use case?
3. RQ3: What conclusions can be drawn about the impact, costs and benefits of deploying small cells in the Utrecht practical case study? To solve this, the following sub-questions are identified:

- SQ3.1: Which stakeholders/actors need to be involved in realising and orchestrating the rollout of small cells?
- SQ3.2: What are the limitations and possibilities for the implementation of small cells?
- SQ3.3: How will the environment, transport network, energy network and underground cabling situation of the researched area be impacted?
- SQ3.4: What is the cost estimated for small cells in the researched area?
- SQ3.5: What other practical aspects affect small cells?

1.4 Methodology

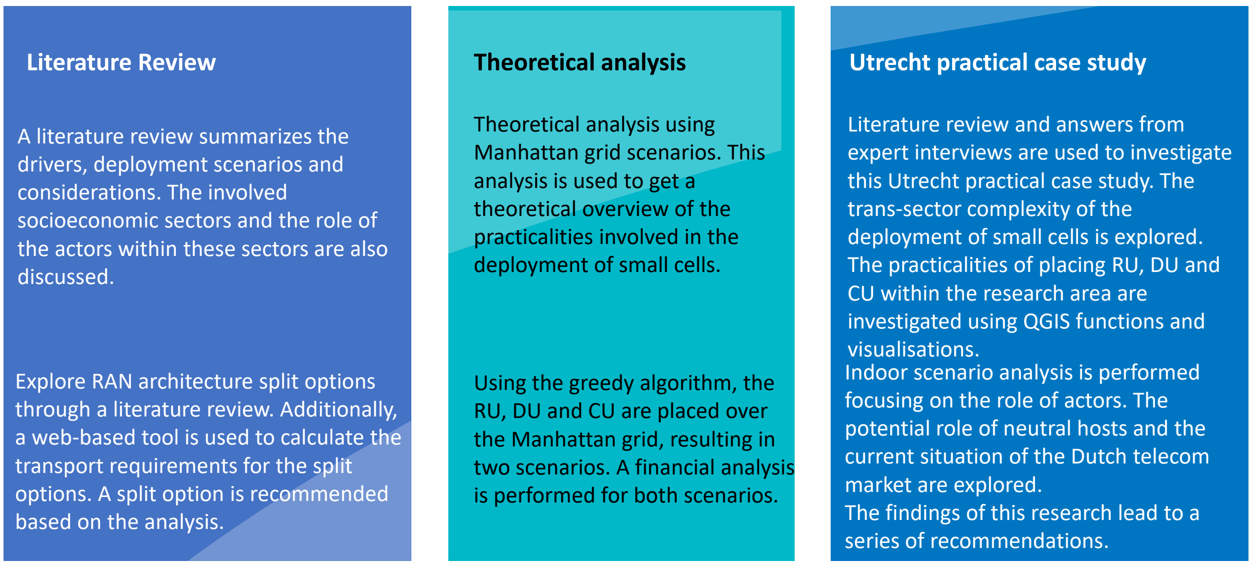

Figure 2: Overall methodology of the master thesis' research

Figure 2 shows the overall methodology followed for the master thesis. Literature surveys from different organisations, especially the Small Cell Forum (SCF) [6] are used throughout this master thesis project. The publications, papers and blogs helped in partially answering RQ1 and RQ2. Meetings and interviews were done with experts from the Municipality of Utrecht to understand the physical and digital properties of Utrecht related to the practicalities involved in the deployment of small cells. The meeting notes from these meetings and interviews were especially helpful for answering RQ1 and RQ3. Apart from that, the report from fellow junior students helped in understanding the roles of the actors as well as the trans-sector value of the implementation of small cells and was integral in answering SQ3.1. Utilising the QGIS software and Google 3D Street View Map for visualisation and analysis for the practical deployment of small cells within the research area was important in answering SQ3.2, SQ3.3, SQ3.4 and SQ3.5. To conduct a comprehensive study for the Utrecht practical case study, the following steps were performed:

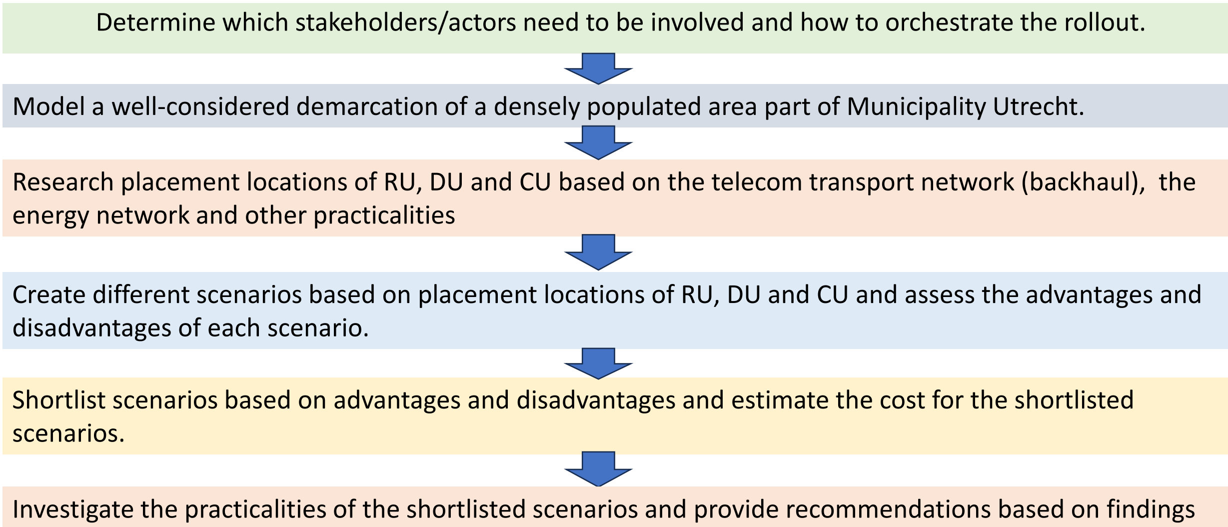

Figure 3: Utrecht practical case study methodology

Figure 3 shows the methodology followed for the Utrecht practical case study. This is further elaborated in Chapter 4 section 4.1.

1.5 Structure of the thesis

Chapter 2 partially answers RQ1 by introducing the drivers and contemporary deployment scenarios for small cells. Section 2.3 partially answers SQ3.1 by introducing the socioeconomic sectors and the actors within, which are expected to be involved in the realisation of small cells. Section 2.6 answers RQ2 by means of a literature review and comparing the split options.
Chapter 3 introduces the theoretical scenarios which give an indication of the cost parameters involved and partially answer RQ1.
Chapter 4 delves into the Utrecht practical case study. Section 4.1.1 and section 4.1.2 analyse the socioeconomic sectors and the role of the actors within and explore the trans-sector nature of this project, solving answering SQ3.1. Section 4.2.3 shows the possible locations for the placement of RU, DU and CU. Section 4.2.4 explains the methodology used for creating the visualisations contributing to a better understanding of the practicalities involved in the deployment of small cells. Section 4.3 gives an overview of the challenges faced by MNOs in providing coverage indoors and explores the role of neutral hosts.
In Chapter 5, section 5.1 discusses visualisation and proposes the possible locations for the installation of RU, DU and CU and performs a financial analysis, answering SQ3.3 and SQ3.4. Section 5.2 summarises the results from the interviews conducted with the experts, which answers SQ3.2 and SQ3.5.
Chapter 6 discusses the research results and joins the main conclusions from Chapters 2-5. Section 6.1 summarises the answers to the research questions and sub-questions. Section 6.2 gives recommendations regarding the Utrecht practical case study and deployment of small cells as well as future academic work.

Chapter 2

Theory and literature review

This chapter gives an overview of the drivers, deployment scenarios and factors to be considered for the deployment of small cells. The involved actors and the socioeconomic sectors to which they belong are also partially discussed in this chapter. Apart from that, the industry-specified split options are introduced and compared to each other.

2.1 Drivers for small cell deployment

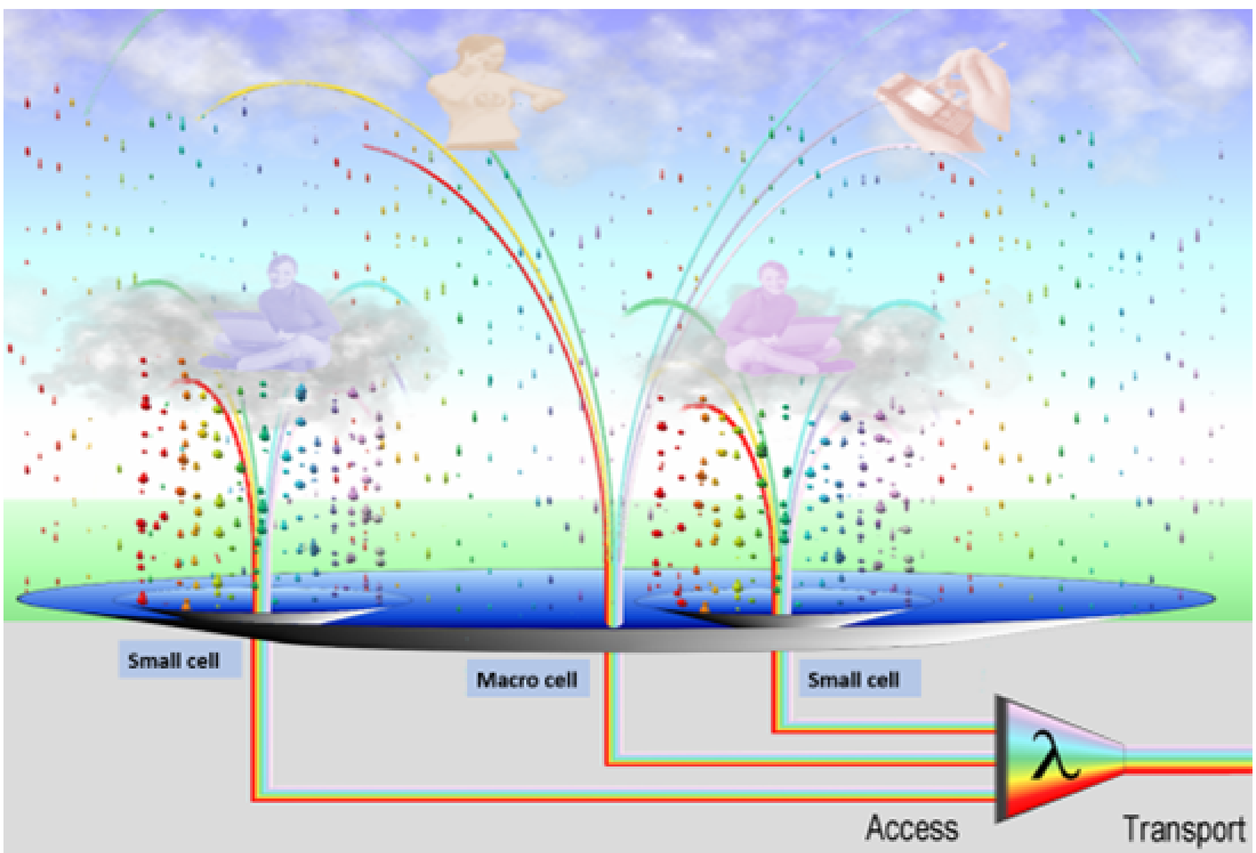

Figure 4: A conceptual view of small cells within a macro cell area

Figure 4 depicts the conceptual view of small cells within a macro cell area [3]. The water drops represent the network capacity in both uplink and downlink directions. The water drops around the small cells are bigger because small cells provide more capacity than macro cells by making use of higher frequency waves and their characteristic short radio range [2]. The small cells under the blanket of macro cell coverage will strengthen the network capacity within a short range. Higher frequency means shorter radio ranges. These small cells will help in offloading the macro network usually in densely populated areas. Therefore small cells need to be placed in well-considered geographical sub-parts within the macro cell.

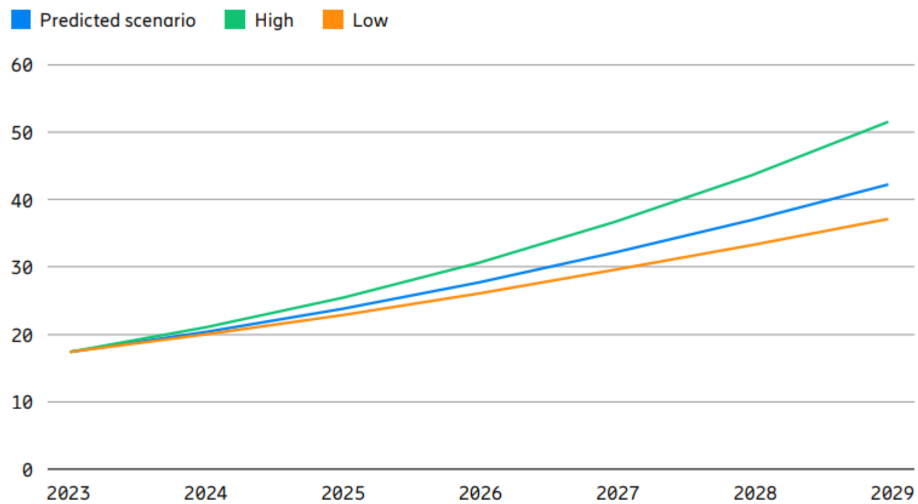

Figure 5: Global mobile data traffic per active smartphone (GB per month) scenarios [7]

Globally, the increase in mobile data traffic volume per smartphone (shown in figure 5) can be attributed to three main drivers: improved device capabilities, an increase in data-intensive content, and growth in data consumption due to continued improvements in the performance of deployed networks [7].
The primary drivers for small cell deployment are improving network capacity and lowering energy consumption. From the perspective of telecom operators, the demand for increased capacity is a significant motivator for deploying small cells, especially as high-frequency waves are introduced. Small cells can efficiently boost cellular capacity in a given area by providing a better signal-to-interference-plus-noise ratio (SINR) and a smaller coverage footprint, which reduces the sharing of cell resources [10]. As a result, devices connected through small cells can achieve higher throughput compared to those connected via macro cells.

In addition to enhancing capacity, small cells also contribute to lowering energy consumption, which is becoming increasingly important given the rapid growth in the use of AI and other digital networks [10]. Small cells consume significantly less power compared to macro base stations due to a reduced coverage area (e.g. less transmitting power) and the less requirement for site support infrastructure (e.g. cooling systems) [10]. Reducing energy consumption is essential for building a sustainable future, and the relatively low energy demands of small cells can help to reduce the carbon footprint of mobile networks. Moreover, small cells open up possibilities for utilising renewable energy sources in network operations [10].

Small cells can provide reliable connections both indoor and outdoor, particularly in urban settings improving outdoor network capacity in the hotspots in a macro cell. They also enhance spectrum efficiency by making better use of existing spectrum, allowing spectrum license holders to extract more value from their assets. Furthermore, the compact and visually unobtrusive design of small cells makes them ideal for widespread deployment without negatively impacting the aesthetics of the built environment, including its monuments and iconic buildings [10].

2.2 Deployment scenarios

Outdoor deployment involves placing small cells in public spaces such as crowded streets and parks to enhance network capacity in these high-traffic locations. Outdoor small cells are typically installed on existing infrastructure, like lamp posts or utility poles, where they can efficiently support the macro network by providing localized coverage and better signal quality in areas where the macro network alone might not be enough due to high user density or challenging environments [10].
Indoor deployment focuses on enhancing coverage within buildings, such as offices, shopping malls, airports, and residential complexes. Indoor small cells are crucial for ensuring strong and reliable connections in environments where the macro network's signals may be weakened by walls or other obstacles [12].

2.3 Deployment considerations for small cells

In the context of deployment considerations for small cells, one crucial aspect is spectrum allocation. For network densification, newly allocated or targeted spectrum bands are envisioned for 5G New Radio (NR), particularly in the mid-bands between 3 and 7 GHz [10]. The availability of spectrum in the sub-3 GHz range is constrained due to the presence of various other wireless systems operating in the same range. This limitation hinders network densification, as the spectrum needs to be reused or shared between macro and small cells.

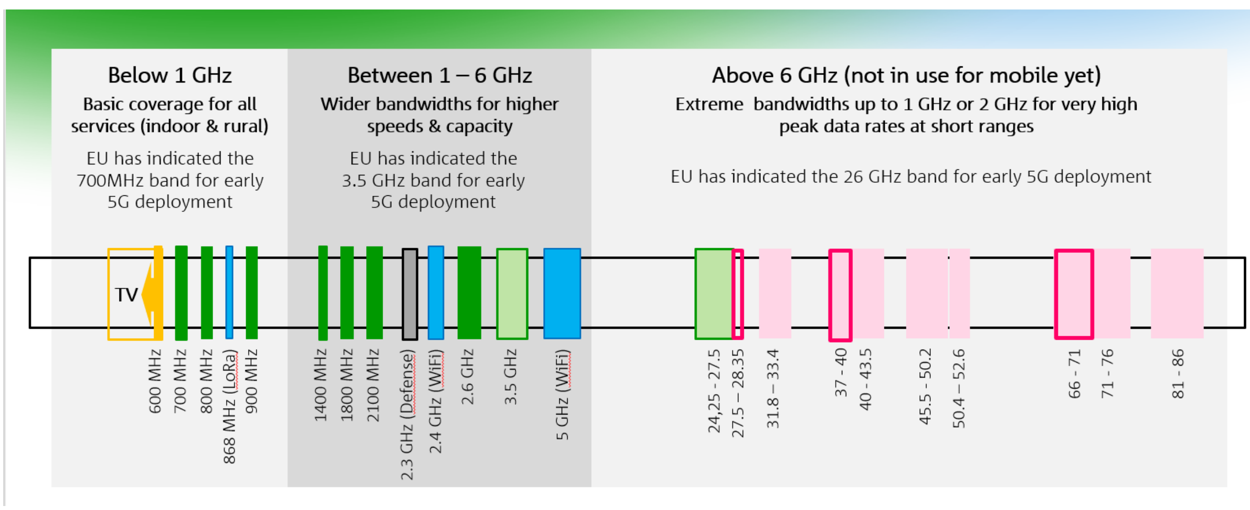

Figure 6: Spectrum Bands

As seen in the above figure 6, the 3.5 GHz band is a newly acquired frequency band in the Netherlands for 5G and is to be utilised by all MNOs. In addition to the mid-band allocations, future high band allocations in the millimetre wave (mmWave) bands, typically above 24 GHz, are poised to offer even wider contiguous bandwidths, with some bands providing up to 3 GHz of spectrum. The EU has indicated the 26 GHz band will be utilised in 5G deployment. The availability of the higher frequency bands 3.5 GHz and 26 GHz is integral in the densification of the network with small cells.

Limitations in backhaul link capacity can create bottlenecks for the capacity provided by base stations utilising these links. Additionally, delays over the backhaul and fronthaul links contribute significantly to the end-to-end latency experienced by end users provided via the mobile and fixed networks.

5G networks are designed to support heterogeneous service types with varying performance requirements, necessitating enhancements in fronthaul and backhaul link performance. These enhancements must accommodate the increased data traffic demands of enhanced mobile broadband, the scalability requirements of massive machine-type communications, and the stringent latency and reliability demands of ultra-reliable low-latency communications.

Powering considerations play a crucial role in the deployment of small cells, particularly in the context of 5G networks. Small cell products are inherently more energy-efficient compared to macro base stations due to their reduced coverage area and lower demand for site support infrastructure, such as cooling systems. However, the increased network densification in 5G, necessitating more sites that require powering, results in an overall rise in network-wide energy consumption [10].

Mobile network infrastructure sharing takes a number of forms, including contractual agreements or joint ventures between independent MNOs. An increasingly common approach is the outsourcing of the provisioning of certain site infrastructure and/or infrastructure services (e.g. site maintenance) to third-party providers. Infrastructure sharing is even more critical for small cell networks due to the required density of deployment and the wider diversity of deployment scenarios [10].
The deployment and operation of Radio Frequency (RF) transmitters, such as small cells, raises safety considerations due to human exposure to Electro Magnetic Fields (EMF). Human exposure to EMFs is actually a regular occurrence in daily life due to the ubiquitous presence of EMF sources across the electromagnetic spectrum and can be attributed to both natural sources (e.g. the sun), as well as, artificial EMF sources (televisions, wireless networks, etc.). The concerns of local authorities and communities on visual pollution by base stations are particularly acute in the cases of preserving:

- Urban skyline and landscapes
- Local architectural style
- Landmarks
- Historical buildings and other heritage sites
- Parks and public gardens
- Nature reserves and conservation areas
- Areas of special scientific interest

These concerns about visual pollution and their influence on the decisions to grant planning permits for base station deployment have obliged mobile equipment vendors and MNOs to take active measures to reduce the visual impact of base stations [10].

2.4 Involved stakeholders

Deploying small cells involves eight socioeconomic sectors and the actors within these sectors. The roles of all the actors are detailed in this section. The involved stakeholders in the deployment of small cells are the following:

- Government:
  - Municipalities: Municipalities play a crucial role in the rollout of small cells. They are responsible for preserving the aesthetics of the city, preventing irreversible damage to infrastructure, and minimizing disruptions for pedestrians and cyclists. In some cases, municipalities may also own the local power grids, making them key collaborators with Mobile Network Operators (MNOs) and energy companies in planning for the power requirements of small cells. Municipalities establish guidelines and grant permits while considering factors like aesthetics, infrastructure protection, public convenience, and infrastructure sharing potential. Additionally, municipalities issue permits for road access required during installation, ensuring minimal disruption. This may involve restricting installation to off-peak hours and enforcing strict timelines for completion. To foster collaboration and trust among all actors, municipalities can promote open communication through platforms for dialogue involving MNOs, residents, and other key participants. Moreover, municipalities can address public concerns about 5G by providing accessible, science-backed information through widely-used platforms like the municipality's own website, in addition to those already maintained by national entities.

  - National Regulatory Authorities (NRAs): NRAs, operating under the National Government, ensure compliance with regulations related to small cell installation, operation, and safety standards. They develop national guidelines, which municipalities can adapt according to their local needs. Key NRAs in the Netherlands include the Dutch Authority for Consumers and Markets (ACM) and the Dutch Authority for Digital Infrastructure (RDI).
  - EU Policymakers: EU policymakers focus on harmonizing regulations across member states, creating overarching guidelines for mobile operators. National regulators then develop specific frameworks based on these EU guidelines to cater to their countries.
  - Standardisation Organisations: Bodies such as the International Telecommunication Union (ITU) and the 3rd Generation Partnership Project (3GPP) are responsible for developing technical standards that ensure interoperability across various equipment and network components. Manufacturers and MNOs must adhere to these standards to enable a seamless rollout and consistent user experience.
  - Kadaster: Kadaster (Land Registry in the Netherlands) is a government service that keeps records of parcels of land, buildings, movable registered property, the rights and rights holders, addresses and other geographical [30]. Kadaster carries out tasks under the responsibility of the Ministry of the Interior and Kingdom Relations [30]. When installing small cells, especially in urban areas with dense underground infrastructure, mobile network operators (MNOs) and municipalities are required to notify Kadaster before any mechanical digging through the Klic (Cable and Pipeline Information Centre) system. This notification process is essential for safeguarding underground utilities, as it helps prevent accidental damage and costly disruptions.

- Communications:
  - Mobile Network Operators (MNOs): MNOs are engaged throughout the entire deployment process, from network planning and obtaining approvals to post-deployment maintenance. Their objectives include ensuring adequate capacity, minimizing interference, and optimizing deployment costs, all while adhering to the rules and regulations set by municipalities.
  - Fixed Network Operator: Fixed network operators are responsible for deploying and maintaining the underlying wired infrastructure (fibre, copper, etc.) that connects small cells to the core network. They ensure that small cells have reliable backhaul connections, which are essential for data transport between small cells and the core network.

- Real-estate:
  - Landlords: Permission from landlords is required to install small cell equipment at ideal locations. In exchange, landlords may receive rental income from telecom providers. However, landlords may also have concerns about the aesthetics of the installation, potential interference with existing equipment, or health risks associated with exposure to electromagnetic radiation from telecom equipment.
  - Neutral host: Neutral hosts are companies that invest in telecommunications infrastructure, such as small cells, real estate, and fibre networks, and provide open access to all MNOs operating in a given location. In small cell projects, neutral hosts can own and lease small cell equipment to MNOs, facilitating a more efficient and cost-effective deployment.

- Manufacturing:
  - Manufacturers: Telecommunications equipment manufacturers produce the hardware and devices used in small cell deployments, including modems, switches, routers, base stations, and power equipment. Manufacturers are responsible for designing and building the small cell infrastructure, ensuring it meets technical standards set by organizations such as the ITU and 3GPP.
- Energy:
  - Energy Companies: As small cells may outnumber macro cells in the long term, a reliable energy supply becomes critical. Energy companies need to offer cost-effective solutions for powering small cells, potentially by leveraging existing infrastructure. This, however, involves negotiations with building owners, tenants, and local authorities. Additionally, backup power systems such as batteries or diesel generators are necessary for small cells in critical areas, which may require additional permits and space.
- Households
  - End users: End users are the consumers of the telecom services provided via small cells. They expect benefits such as improved coverage and reduced network congestion. Some may have concerns regarding health risks associated with Radio Frequency (RF) waves, as well as the impact on the city's aesthetics.
- Professional Activities:
  - Consultants: The consultants hired by the municipality will help in site planning for the small cell project. Due to their knowledge of the domain, they will advise the other actors about the possibilities of the location of small cells.
- Construction:
  - Equipment Installers: Installers are responsible for setting up, rearranging, or removing small cell equipment, including backhaul cabling, power supply, and the installation of the small cells themselves. In cities with historic significance, installers must ensure that the city's aesthetics and structural integrity are preserved during and after installation.

A visualisation of all the sectors and actors to show the trans-sector nature of this project is provided in Chapter 4, section 4.1.

2.5 Split options

Disaggregation of RAN and Small Cell Networks (SCN) brings several advantages: such as efficient operation of remote radio units via centralized units, gains of pooling centralized resources, potential cost reduction due to low complexity radio units and shared central units [16].

Radio Resource Control
Packet Data Convergence Protocol
High-Radio Link Control
Low-Radio Link Control
High-Medium Access Control
Low-Medium Access Control
High-Physical
Low-Physical
Radio Frequency

Figure 7: 5G RAN architecture layers

By splitting the 5G RAN architecture layers shown in figure 7, there are many split option possibilities. This thesis project deals with the three industry-specified split options (2, 6 and 7.2) as well as split option

8 which is implemented for LTE. This section also looks into the transport requirements for the four split options with the help of a web-based tool provided by Small Cell Forum (SCF), known as the disaggregated RAN transport study (DARTs) tool. Transport requirements are an integral factor in choosing an optimal split option and are key to determining overall CAPEX requirements. The DARTs tool calculates the transport requirements based on assumed parameters set by the user. The parameters assumed for this analysis are: NR TDD site with air interface bandwidth of 60 MHz and 4T*4R antenna configuration [6].

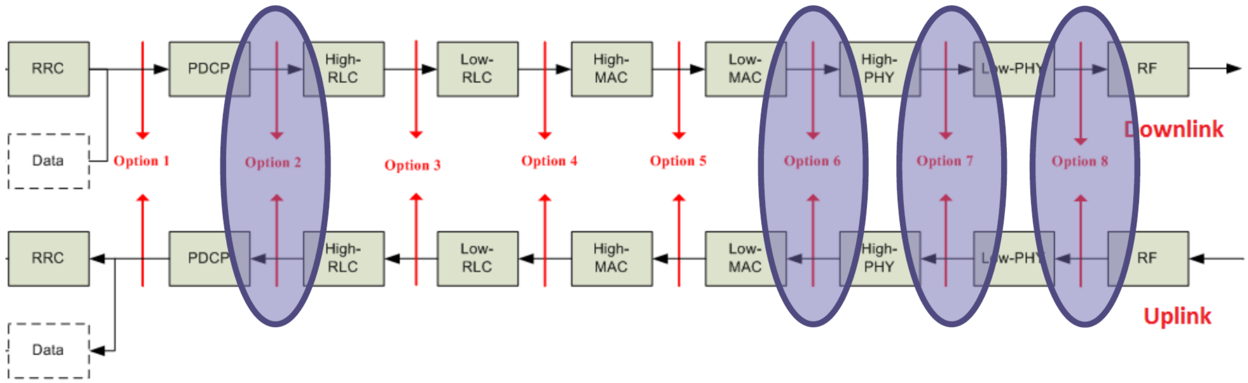

Figure 8: Industry specified split options for disaggregated RAN [6]

The above figure 8 highlights the split options used in the thesis. Split option 2 is referred to as a High Layer Split (HLS) whereas split options 6, 7.2x and 8 are Low Layer Split (LLS) options. A low-layer split demands a higher fronthaul bandwidth and is less delay-tolerant than a high-layer split. However, a low-layer split offers coordination and subsequent performance benefits [16]. The optimal network split is deployment scenario-dependent [23].

Split option 2

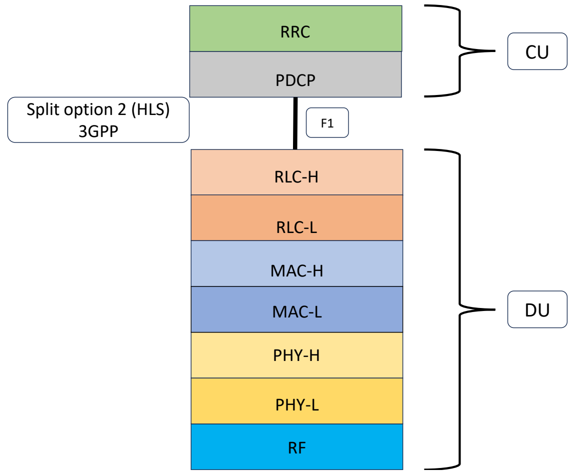

Figure 9: Split option 2

The 3GPP standard defines a higher layer split option 2 architecture (shown in figure 9), which utilises the F1 interface to connect the gNB-CU (Central Unit) and one or more gNB-DUs (Distributed Units) [12].

- CU: The gNB-CU manages PDCP and RRC protocols.
- DU: The gNB-DU(s) manages RLC, MAC, PHY, baseband and RF processing.

This architecture has the advantage of supporting low throughput and being delay-tolerant for the 3GPP F1 interface. This compatibility allows the use of existing Ethernet and other legacy transport infrastructures. However, the gNB-DUs have more complex functionality than other remote units, and the coordination benefits are less pronounced than those seen with lower layer splits [23]. The transport requirements for split option 2 are realised using the DARTs tool [6]. For a user to achieve a peak throughput of 1169 Mbps in the downlink direction and 164 Mbps in the uplink direction, the transport requirements for the split option 2 are the following:

- Downlink
  - Backhaul transport requirements between the CU and core network is 1405 Mbps.
  - Midhaul transport requirements between CU and the DU is 1341 Mbps.
- Uplink
  - Backhaul transport requirements between the CU and core network is 198 Mbps.
  - Midhaul transport requirements between CU and the DU is 189 Mbps.

Split option 6

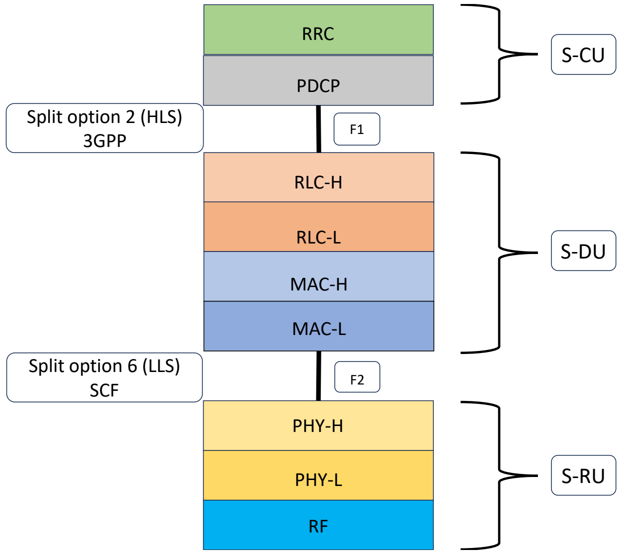

Figure 10: Split option 6

Split option 6 (shown in figure 10) is a lower-layer split and is promoted by the Small Cell Forum. Therefore the architectural elements are termed as S-RU, S-DU and S-CU.

- S-CU: The central unit manages the PDCP and RRC protocols.
- S-DU: The distributed unit manages RLC and MAC.
- S-RU: The radio unit manages the PHY, baseband and RF processing.

. For split option 6, the higher layer S-CU/S-DU logical functions can be combined into a single unit or kept separated with the 3GPP F1 upper layer split option 2. Split option 6 tends to be more popular in indoor enterprises and private networks [23][6]. Similarly, the DARTs tool is used to calculate the following transport requirements for split option 6. For a user to achieve a peak throughput of 1169 Mbps in the downlink direction and 164 Mbps in the uplink direction, the transport requirements for the split option 6 are the following:

- Downlink
  - Backhaul transport requirements between the CU and core network is 1405 Mbps.
  - Midhaul transport requirements between CU and the DU with transport overhead is 2076 Mbps.
- Uplink
  - Backhaul transport requirements transport requirements between the CU and core network is 198 Mbps.
  - Midhaul transport requirements between CU and the DU is 1043 Mbps.

Split option 7.2x

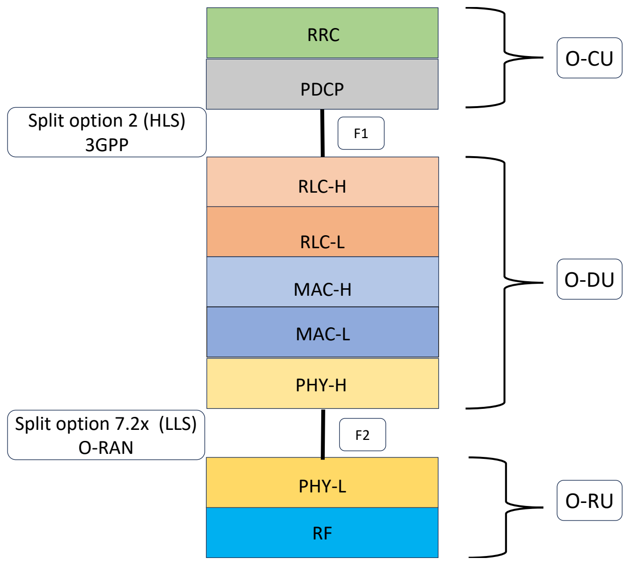

Figure 11: Split option 7.2x

The split option 7.2x (shown in figure 11) is promoted by the O-RAN Alliance and the architectural elements are termed as O-RU, O-DU and O-CU. Split option 7.2x solutions are defined by the O-RAN Alliance organisation as an open fronthaul interface between the O-DU and O-RU, which uses the eCPRI protocol specification [23].

- O-CU: The central unit manages the PDCP and RRC protocols.
- O-DU: The distribution unit manages the RLC, MAC and high-PHY protocols.
- O-RU: The radio unit manages the low-PHY(FFT/iFFT), baseband and RF networks.

For a user to achieve a peak throughput of 1169 Mbps in the downlink direction and 164 Mbps in the uplink direction, the transport requirements for the split option 7.2x are the following:

- Downlink
  - Backhaul transport requirements between the CU and core network is 1405 Mbps.
  - Midhaul transport requirements between CU and DU is 4876 Mbps.
- Uplink
  - Backhaul transport requirements between the CU and core network is 198 Mbps.
  - Midhaul transport requirements between CU and DU is 2438 Mbps.

Split option 8

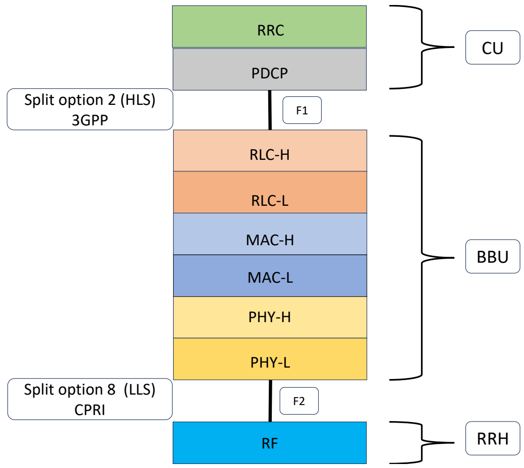

Figure 12: Split option 8

Split option 8 (shown in figure 12) commonly used in the industry is implemented in LTE and some early 5G deployments, especially by MNOs in China where fronthaul fibre is readily available. This approach utilizes a proprietary CPRI specification for the fronthaul interface [23].

- CU: The central unit includes the PDCP and RRC protocols.
- BBU: The distributed unit includes the RLC, MAC and PHY protocols.
- RRH: The remote radio head only includes the RF processing.

Split option 8 uses the proprietary CPRI interface. For split option 8, the CU and BBU can be stacked together or kept separated with the 3GPP F1 upper layer split option 2 [23]. For a user to achieve a peak throughput of 1169 Mbps in the downlink direction and 164 Mbps in the uplink direction, the transport requirements for the split option 7.2x are the following:

- Downlink
  - Backhaul transport requirements between the CU and core network is 1405 Mbps.
  - Transport requirements between RU and CU is 12165.12 Mbps.
- Uplink
  - Backhaul transport requirements between the CU and core network is 198 Mbps.
  - transport requirements between RU and CU is 112165.12 Mbps.

The four split options discussed in this thesis can be deployed in different environments depending on the requirements of the deployment scenario.

Table 1: Split Options and use cases [23]

Split option	**Use Case**
Split option 2	popular in North America for both indoor and outdoor, including private and hotspot deployments
Split option 6	popular in the indoor enterprise and private networks
Split option 7.2x	popular in outdoor urban and rural small cell networks.
Split option 8	popular in China for indoor enterprise

2.6 Comparison of split options

This section will compare the four split options based on transport requirements, use cases and costs.

Table 2: Transport requirements for split options in Mbps

Throughput	Split option 2	Split option 6	Split option 7.2x	Split option 8	Backhaul
Downlink	1341	2076	4876	12165.12	1405
Uplink	189	1043	2438	12165.12	198

The above table 2 gives an overview of the transport requirements for the split options, which are calculated using the DARTs tool [6]. If most of the RAN components are at the cell site (e.g., as in split option 2), the requirement on the transport network is not stringent (as shown in 2) although the transport network is needed to carry backhaul traffic from the cell site to the core network. Split option 2 deployments take away the advantages of a centralised RAN. This means it is of fundamental importance to consider the design of transport networks alongside the choice of the specific disaggregated architecture to avoid the transport becoming a bottleneck (both in terms of technology and cost) [6].

If most of the RAN components are centralised (e.g., as in split option 8) this imposes stringent requirements on the fronthaul transport network, which transports the raw in-phase/quadrature-phase (I/Q) samples from the RUs to the DUs for processing. Commonly, this fronthaul network is implemented based on the Common Public Radio Interface (CPRI) standard, which requires data rates of up to 24 Gbps per cell [6]. These requirements can only be realised with high-capacity fibre or point-to-point wireless links, making the deployment of the fronthaul network very costly [12].

At this point, split option 2 and split option 8 are not taken into consideration anymore due to the disadvantages in terms of transport requirements. According to SCF surveys, split option 6 and split option 7.2x have been the most popular split options for disaggregated small cell deployment [23]. So from this point forward, split option 6 and split option 7.2x are compared. The main difference between split option 6 and split option 7.2x is where Layer 1 (L1) processing takes place. For split option 6, the physical (PHY) layer functions run entirely on the RU whereas for split option 7.2x, the PHY layer functions are split between RU and DU.

Table 3: Advantages and disadvantages of split options 6 and 7.2x [12]

<table>
<tr><th>Split Options</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td rowspan="3">Split option 6</td><td>Low load on fronthaul because PHY layer is not split – Ethernet can be used and non-ideal connections such as low-grade fibre or microwave</td><td>RU complexity to support PHY</td></tr>
<tr><td>RF Testing and verification more straightforward as PHY is not split</td><td>Reduced flexibility for coordination between cells</td></tr>
<tr><td></td><td>Non-ideal fronthaul may not support Massive MIMO</td></tr>
<tr><td rowspan="2">Split option 7.2x</td><td>Simple and low cost RUs are possible, extending the price options</td><td>High load on fronthaul because of communication between high and low PHY functions based on eCPRI – very high end fibre is necessary, adding to cost</td></tr>
<tr><td>Support for Massive MIMO</td><td>Limited range of RU form factors, limited support for integrated small cells</td></tr>
</table>

The above table displays the advantages and disadvantages of split options 6 and 7.2x. In this study, based on literature review the following advantages of split option 7.2x has been determined:

- Virtualisation of layers: The high-PHY layer in the DU can be virtualised to allow cloud-based coordination between multiple base stations [12].
- Cost-Effective Radio Unit (RU) Designs: This split enables simpler and more cost-effective RU designs, compared to Split option 6, facilitating wider adoption and deployment. In dense urban areas, where numerous small cells are required to ensure coverage and capacity, having affordable, scalable, and easily maintainable RU designs is advantageous [15].
- Minimized Transport Bandwidth Impact: Split option 7.2x reduces the impact on transport bandwidth while maximizing the virtualization capabilities of the gNB Central Unit (CU) and Distributed Unit (DU). This efficiency in transport requirements is crucial for dense urban areas where bandwidth resources are often limited and heavily utilized.
- This disaggregation of hardware and the virtualization of RAN Network Functions (NFs) enables the pooling of RAN resources and NFs, such as the Central Unit (CU) and Distributed Unit (DU), in a centralised pool to support multiple cell sites [9].
- Enhanced Scalability and Flexibility: The ability to centralize and pool resources makes it easier to scale and adapt the network according to varying demand patterns [6].
- Open fronthaul: The O-RAN Alliance promotes split option 7.2x as well as a multi-vendor (open) fronthaul interface through the eCPRI protocol. This ensures interoperability between different vendors' equipment.
- eCPRI protocol: Due to the eCPRI protocol increased efficiency through a packet-based fronthaul network is enabled, for example, IP or Ethernet [12]. Additionally, because of eCPRI the amount of data to be transported scales with the user traffic [24].
- Supports advanced RAN features such as massive MIMO [10], which is critical for enhancing capacity and coverage in dense urban locations.

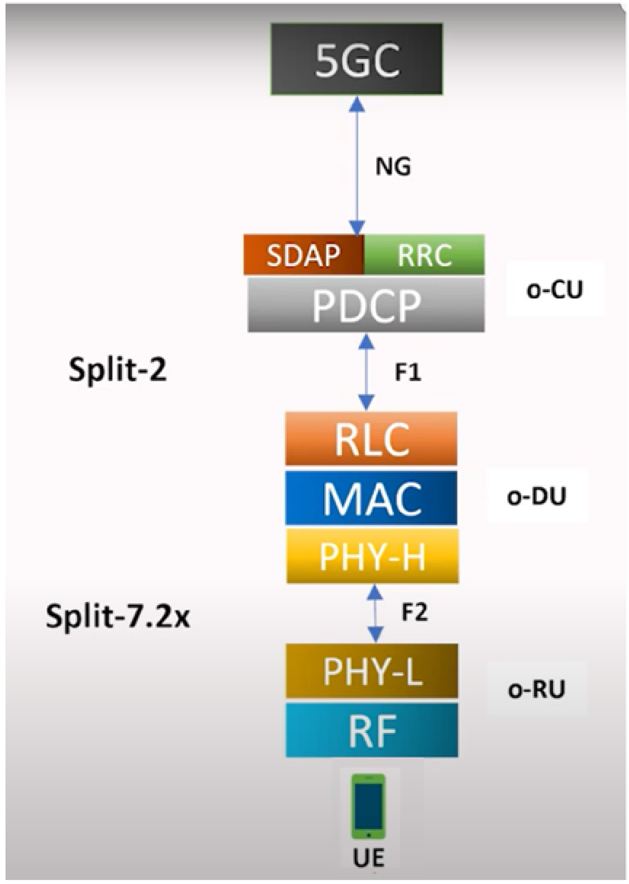

Figure 13: Architecture of split option 7.2x

The above figure 13 visualises the architecture of the split option 7.2x. Based on these parameters split option 7.2x can be preferred as an optimal split option for the outdoor dense urban area like the Utrecht city centre. The disaggregated architecture will ensure that the CU and DU can be collocated as a single unit or separated units in an indoor environment (for example wharf cellar), protected from the weather and possibility of vandalism. On the other hand, the implementation of RU should be cheaper compared to other higher-split options. Split option 7.2x can be considered as the optimal option for different types of indoor settings for the same reasons stated above.

2.7 Summary

The deployment of small cells is primarily driven by the need to significantly improve network capacity and reduce energy consumption, especially as the need for network densification keeps increasing. For telecom operators, the demand for increased capacity is a critical motivator, particularly with the introduction of high-frequency waves that offer greater bandwidth but provide shorter coverage. Small cells address this need by offloading the macro network and reducing the strain on cell resources which enables devices connected to small cells to achieve higher throughput compared to those relying on macro cells.

In addition to enhancing capacity, small cells play a vital role in reducing energy consumption, which is increasingly important in the context of the rapid expansion of AI and other digital networks. As the demand for digital services grows, so does the need for sustainable solutions to manage the associated energy consumption. Small cells, being inherently more energy-efficient compared to macro base stations due to their reduced coverage area and lesser requirement for site support infrastructure, offer a way to reduce the carbon footprint of mobile networks while maintaining the necessary performance levels. Furthermore, small cells present opportunities to incorporate renewable energy sources into network operations, contributing to the goal of sustainability and making networks future-proof.

Section 2.4 partially answers SQ3.1 by detailing the roles of the actors within the eight socioeconomic sectors involved in the deployment of small cells.
Section 2.5 shows the many possibilities for split options. Out of them Split options 2, 6 and 7.2x are industry specifies by 3GPP, SCF and O-RAN Alliance respectively and split option 8 was popular in early deployments of 5G and LTE. Therefore these four split options are shortlisted and analysed in more detail.
Section 2.6 compares the transport requirements for the four split options, using the DARTs tool. Based on that split options 2 and 8 were not considered for further analysis. Split option 6 and split option 7.2x are analysed based on advantages, disadvantages, use cases and costs. Split 7.2x is recommended as the optimal option for indoor and outdoor environments therefore answering RQ2.

Chapter 3

Theoretical scenario analysis

This chapter gives an overview of two theoretical scenarios using the Manhattan grid to glimpse into the practicalities involved in the deployment of small cells. In section 3.2, the financial analysis of the theoretical scenarios is done to get an indication of the costs involved.

3.1 Manhattan grid scenarios

The scenarios in this section provide a theoretical overview of the placement of the architectural elements as well as the cost estimation for the placement of small cells. These theoretical scenarios are assessed later to see how the cost estimations can match the Utrecht practical case study, which will be discussed in Chapter 5, section 5.2. For this analysis, a Manhattan grid is used as a template. In most of Manhattan (and a few neighbourhoods in the outer boroughs), thoroughfares are mapped out on a grid system where streets and avenues run perpendicular to each other [13]. This Manhattan grid was chosen for its simplicity and its ability to provide a theoretical overview for the optimal placement of RUs, DUs, and CUs. Steps taken for the analysis of scenarios:

- All the RUs were placed at the intersections of four line segments.
- Then based on the greedy algorithm, the DUs followed by the CUs were placed
- A list of assumptions was made for each of the scenarios.
- A list of assumptions was made for the cost of the components and activities involved with the installation of small cells.
- The cost estimation was done for each scenario to be compared for later analysis.

3.1.1 Wired scenario

In the wired scenario, it is assumed that all the architectural elements of small cells (RU, DU and CU) need to be connected with fibre. The cost of fibre and cable is not considered as it is minimal when compared to digging costs. The following assumptions were made when setting up the scenario for cost analysis.

- All RUs, DUs and CUs need to be served with power and fibre connection.
- All RUs will be connected to a DU. For this example, five RUs need to be connected to one DU.
- All DUs will be connected to a CU. For this example, five DUs need to be connected to one CU.
- A power supply is present at the position of every CU.
- Digging is only done once for setting up cables.
- Only digging costs are considered.

- Fibre and cable costs are not considered.

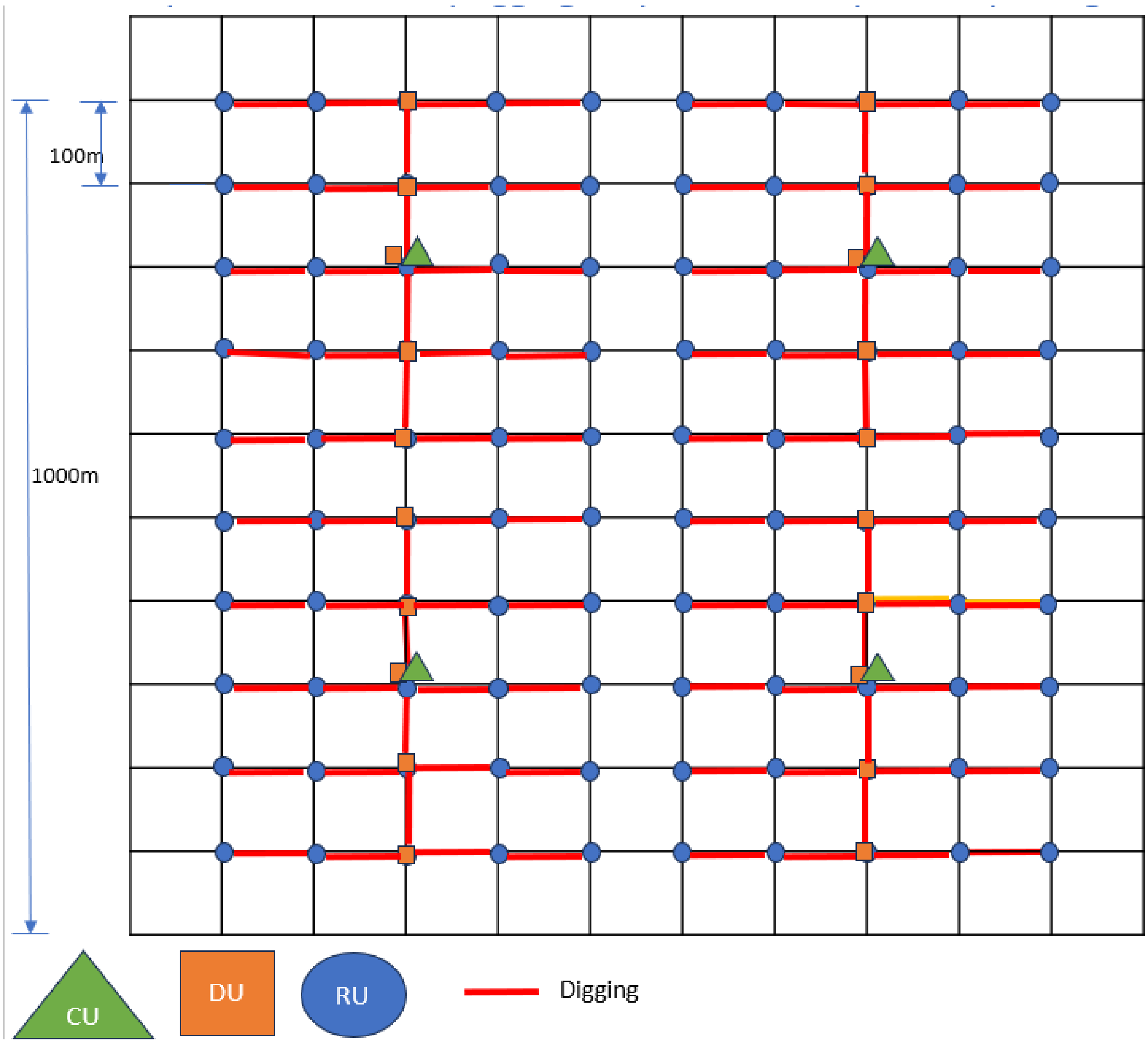

Figure 14: Wired Manhattan grid scenario

The positioning of the CUs and DUs is done using the Greedy algorithm (shown in figure 14). Greedy algorithms are a class of algorithms that make locally optimal choices at each step with the hope of finding a global optimum solution. In these algorithms, decisions are made based on the information available at the current moment without considering the consequences of these decisions in the future [14]. It uses a bottom-up and an inside-out approach. This indicates that all the lower levels of the hierarchy and the shortest distance were connected first. That means all the RUs were first connected to the DU based on the shortest distance followed by the DUs getting connected to the CU. The code for the greedy algorithm is provided in Appendix E.

3.1.2 Wireless scenario

In the wireless scenario, it is assumed that the RUs will be connected to a DU by a wireless ad-hoc network and the DUs will be connected to the CUs by fibre. The RUs will be powered by solar panels and batteries, making them more energy-efficient. The cost of fibre and cable is not considered as it is minimal when compared to digging costs. The following assumptions were made when setting up the scenario for cost analysis:

- All RUs will be connected to a DU. For this example, five RUs are connected to one DU.
- All DUs will be connected to a CU. For this example, five DUs are connected to one CU.
- A power supply is present at the position of every CU.
- Digging is only done once for setting up cables.
- Only digging costs are considered.
- Five RUs are connected to their corresponding DU using a wireless ad-hoc network.
- Fibre and cable costs are not considered.

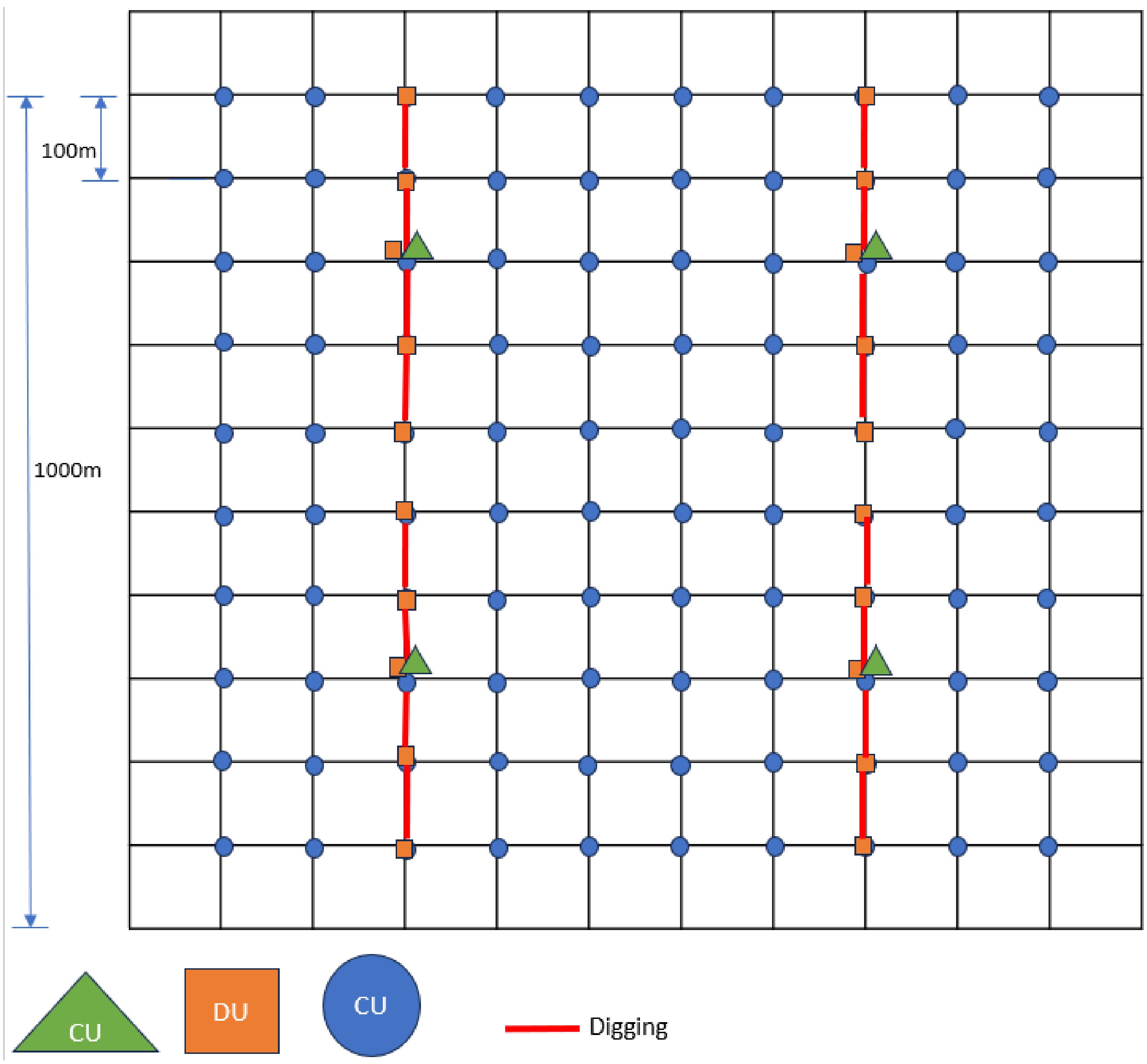

Figure 15: Wireless Manhattan grid scenario

The positioning of the CUs and DUs is done using the Greedy algorithm (shown in figure 15). As outlined in Chapter 2, Section 2.6, split option 7.2x is recommended as the optimal choice for urban deployment due to its advantages in virtualization capabilities and cost efficiency. Implementing split option 7.2x with a wireless fronthaul connection is feasible in dense urban areas when higher frequency bands (mmWave bands) are employed [27].

3.2 Financial analysis

For the two scenarios mentioned above, it was necessary to get an indication of the parameters that might contribute to the overall cost of deployment. The costs of the RU, DU, CU, digging and solar panels were considered for this analysis. The costs mentioned in the table are theoretical assumptions made by experts and might vary in the Utrecht practical case study.

Cost estimations for wired scenario

The following cost assumptions were made for this scenario:

- Digging/100 meter = €5000

Table 4: Cost estimation for wired scenario

	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	25	125000
DU	2500	5	12500
CU	5000	1	5000
Digging/100m	500	24	120000
Total Cost			**262500**

Cost estimations for wireless scenario

The following cost assumptions were made for this scenario:

- Solar panel and batteries = €60
- Digging/100 meter = €5000

Table 5: Cost estimation for wireless scenario

	Cost of 1unit (€)	Number of units required	Total Cost (€)
RU	5000	25	125000
DU	2500	5	12500
CU	5000	1	5000
Solar Panel	60	25	1500
Digging/100m	5000	4	20000
Total Cost			**164000**

From the above two scenarios, it can be observed that digging is the costliest parameter followed by the equipment costs. The cost of the wired scenario is 37% more than the wireless scenario due to the cost of digging for power and transport network. The list of parameters provided an idea of the parameters that will be needed to calculate the cost for the practical scenario of Utrecht in the next chapter.

3.3 Summary

In this chapter section 3.1 analyses two theoretical scenarios created by placing RU, DU and CU in a Manhattan grid. In the first scenario, all the RU to DU connections were made using fibre as opposed to the second scenario where it was assumed that the fronthaul is wireless and RUs are powered by a solar panel to make it energy neutral. Section 3.2 performs a financial analysis of the two scenarios. The cost of the wired scenario exceeds the wireless scenario by €98,500. It is to be noted the cost of digging trenches for fibre is a more expensive factor compared to the solar panels and batteries.

Chapter 4

Practical case study

This chapter describes the problems faced by the Municipality of Utrecht and highlights the complexity of the trans-sector nature of the project. It summarises the pros and cons of possible installation locations of Radio Units (RU), Distributed Units (DU), and Central Units (CU). The chapter also includes an indoor scenario analysis from the perspective of stakeholders and examines the role and benefits of neutral hosts, as well as the landscape of the telecom industry in the Netherlands.

In the Netherlands, there are five degrees of urbanisation based on address density according to data from Statistics Netherlands [25].

- extremely urbanised: 2,500 addresses or more per square kilometre;
- strongly urbanised: 1,500 to 2,500 addresses per square kilometre;
- moderately urbanised: 1,000 to 1,500 addresses per square kilometre;
- hardly urbanised: 500 to 1,000 addresses per square kilometre;
- not urbanised: fewer than 500 addresses per square kilometre.

Out of the above degrees of urbanisation, it is integral to look into the areas under the extremely urbanised category. When high-frequency bands are introduced, these areas will be required to be provided with small cells to serve the need for capacity and offloading the macro network. To contribute to the understanding of the practicalities involved in the deployment of small cells, it is important to analyse a case study dealing with a real location falling under the 'extremely urbanised' category in the Netherlands.

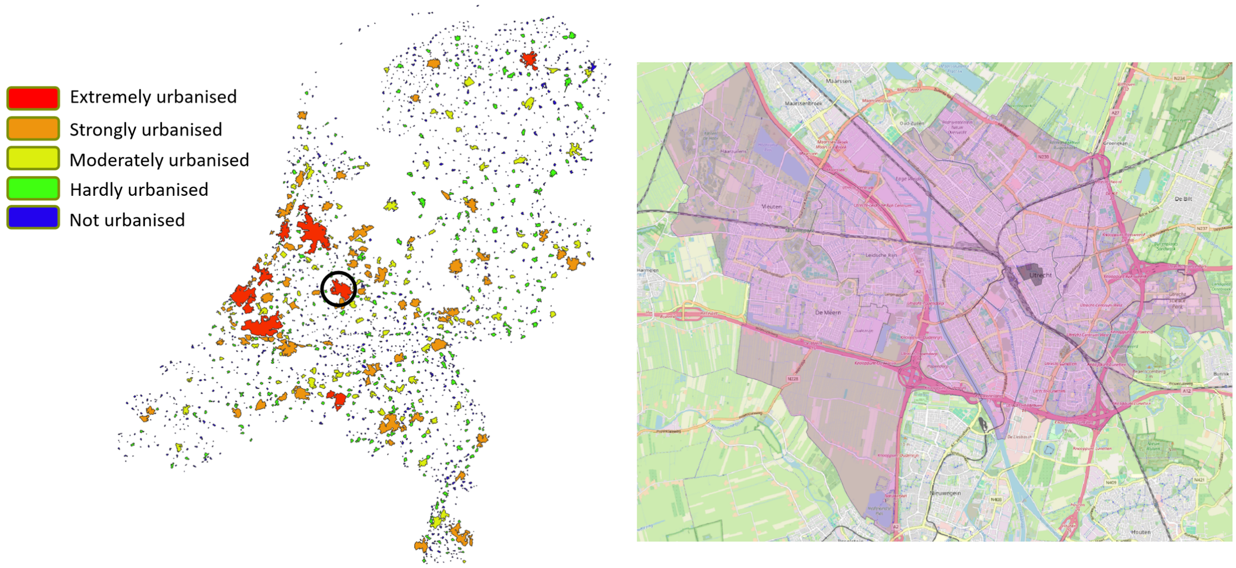

Figure 16: Map of the degree of urbanisation of Dutch municipalities and Utrecht falls under the category of extremely urbanised

This practical case study is based on a selected area in Utrecht, which is under the category of 'extremely urbanised' (see figure 16). The theoretical knowledge gained from the literature review, recommendations from meetings and answers from interviews are used to investigate this Utrecht practical case study.

4.1 Utrecht practical case study description

With the continuous increase in capacity, utilisation of high-frequency bands and the need to provide coverage in all locations in a dense urban area, deployment of small cells seems like the way forward. Therefore the Municipality of Utrecht wishes to timely know the requirements for facilitating small cells, and the feasibility of facilitating a small cell network in practice by means of a joint design process together with all involved stakeholders. In the Utrecht practical case study, the feasibility of small cell deployment is investigated by taking into account practicalities such as the transport network, the power grid, cost estimations, and the municipality rules and requirements. Currently, the Municipality of Utrecht is facing the following issues:

- Difficulties in planning for antenna and small cell deployments due to a lack of guidance on expected numbers. Existing telecom sector guidelines focus on antennas but overlook broader public space impacts, making it challenging to estimate policy investment and ensure cohesive planning.
- Limited control on activities of Mobile Network Operators (MNOs) and energy companies for the installation of antennas and power cabinets in public space.
- Lack of forecasts from telecom operators and energy companies regarding expected increases in traffic volume, the number of small cells required, and associated power needs.
- Avoiding damage to historic sites and hindering the citizens of Utrecht due to digging in public space.
- Limitations in implementing new underground cabling and sinkable power cabinets in the Utrecht city centre, particularly due to the presence of ancient wharf cellars.

Figure 17: underground cables and wharf cellars

4.1.1 Trans-sector complexity and orchestration

The deployment of small cells involves eight socioeconomic sectors [5] and all the actors within it, which makes it a trans-sector project encompassing a very complex combinatorial space.

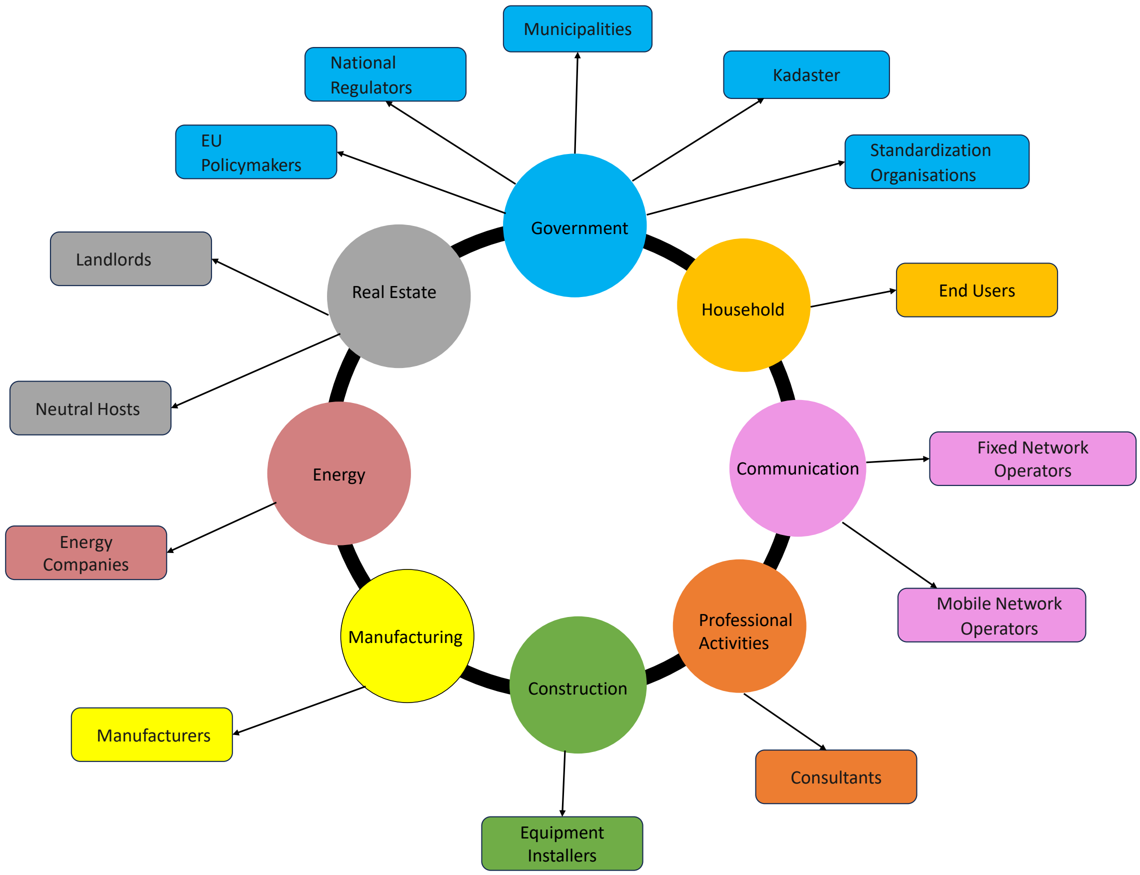

Figure 18: Sectors and related actors contributing to the realisation of small cells

Figure 18 displays all the involved socioeconomic sectors and actors within the sectors [5].

	Government	Household	Real Estate	Communication	Construction	Manufacturing	Energy	Professional Activities
Government	1	1	1	1	1	1	1	1
Household	1	1	0	1	0	0	0	0
Real Estate	1	0	1	1	1	0	1	0
Communication	1	1	1	1	1	1	1	1
Construction	1	0	1	1	1	1	1	0
Manufacturing	1	0	0	1	1	1	1	0
Energy	1	0	1	1	1	1	1	0
Professional Activities	1	0	0	1	0	0	0	1

Figure 19: Unweighted undirected adjacency matrix at sector level

In this research, two unweighted adjacency matrices [29] are created from expert interview input in order to examine the level of complexity of the required collaboration. Figure 19 shows an adjacency matrix A_{ij} at the sector level in which eight sectors are modelled as nodes (N) and their collaboration relations as links (L). Subsequently, Figure 20 shows an adjacency matrix A_{ij} of the collaboration network $G\{N, L\}$ at the actor level. In both adjacency matrices, a 'one' indicates the existence of a collaboration relation and a 'zero' indicates the absence of a collaboration relation between node pairs $(i \neq j)$. Having a value of 'one', the diagonal elements $(i = j)$ indicate node-internal collaboration relations. For example, End Users can join a group aiming to express their worries about health issues from radio antennas and connect to actors belonging to the Government sector, such as municipalities assigned to interact with End Users (interest groups of civilians). The convention in which 'i' represents rows and 'j' represents columns also allows for modelling the direction from i to j for each link. However, for the sake of simplicity in this research, both adjacency matrices provide a simplified symmetric representation of the relations in the real collaboration network in which for example orchestration-related links from regulators are directed.

At the actor level, the unweighted adjacency matrix Aij shown in figure 20 depicts more than 100 links in the collaboration network. This number indicates a need for collaboration agreements and orchestration settlements among the actors in order to realise small cells.The deployment of small cells to densify the network affects the interests of various actors (stakeholders) from different sectors. The sectors involved in the initial, project and maintenance stages of small cells are:

- Government: Municipalities, Kadaster, National regulators, EU policymakers and Standardisation organisations
- Communication: Fixed network operator and Mobile network operators
- Manufacturing: Manufacturers
- Real-estate: Landlords/building owners, Neutral hosts
- Energy: Energy companies
- Construction: Equipment installers
- Professional activities: Consultants

The household sector is the target for the use of small cells and does not belong in the above category. The roles of each of these actors are detailed in section 2.4 of Chapter 2. It can be observed, that the deployment of small cells encompassing eight distinct sectors presents a challenge due to the inherent complexity of coordination required across multiple domains. This trans-sector project faces several implementation difficulties, primarily stemming from the diverse objectives, regulatory frameworks, and operational methodologies unique to each sector. This is in contrast to the deployment of macro cells as it primarily involves two sectors, communication and government. Furthermore, some of these sectors involve more than one actor. This makes it even more complex. There are in total 14 actors stemming from the eight sectors. This results in an extremely complex situation where there can be various possible combinations of actors for the different stages of the deployment of small cells. These combinations are analysed in the following section.

4.1.2 Phased methodology

The complexity of this project can be understood by considering the combinations of actors from different sectors. The more actors involved, the more potential interactions and coordination efforts are required. To analyse the possible combinations of actors without repetition, Newton's binomial theorem is used. This theorem enables calculating the number of different (actor) combinations (for a set of n actors) by expanding the powers of a binomial x + y into a sum of n + 1 terms [4]. The binomial formula can be written as follows:

$$(x+y)^n = \sum_{k=0}^{n} \binom{n}{k} x^{n-k} y^k \tag{4.1}$$

where the binomial coefficient $\binom{n}{k}$ is given by:

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \tag{4.2}$$

In the binomial theorem, setting x=y=1 simplifies the expression to count the total number of combinations of n items, where each item has two possibilities: included or not, resulting in 2n̂ possible combinations. Considering that no actor works alone the possible combination of actors without repetition can be calculated with the formula $(2^n) - (n+1)$, where n is the number of actors involved [4].

In figure 18, it can be observed that 14 actors are involved in the deployment of small cells. Using the binomial theorem, it can be demonstrated that $(2^{14}) - (14 + 1)$ actor combinations are possible. Approximately, 16369 possible combinations result in a complex relation network setting which is difficult to orchestrate. The Utrecht practical case study is an even more complex project. In the context of the Netherlands, the 'MNO' actor can be categorised into three separate actors representing the three MNOs (KPN, Odido, Vodafone). Due to a competitive telecom market, currently these three MNOs do not collaborate to actively share infrastructure and act as separate actors. The MNOs do not find it necessary to cooperate with neutral hosts in the Dutch telecom market at this moment, hence they are not considered as an actor for the Utrecht practical case study. These practicalities increase the involved actors from 14 to 15 and the possible combinations by a factor of two. With 15 actors involved in the practical case study of Utrecht, the possible actor combinations can be calculated as $(2^{15}) - (15 + 1)$, resulting in approximately 32752 combinations, considering that no actors can work alone. Therefore to handle the complexity of this scenario, the analysis for the actor combinations is done for three separate stages of small cells based on the involvement of the actors over time.
The three stages for the integration of small cells in an area are identified, namely, the initial, project and maintenance stages. To understand the possible actor combinations, the actors are divided into these three stages based on their responsibilities described in Chapter 2, section 2.4.

Table 6: Actors involved in the three stages of small cell realisation

Actors	Initial	Project	Maintenance
Municipality	yes	yes	yes
Kadaster	yes	yes	no
National regulators	yes	no	no
EU policy makers	yes	no	no
Standardisation organisations	yes	no	no
Manufacturers	no	yes	yes
Fixed network operator	yes	yes	yes
Mobile network operator	yes	yes	yes
Consultants	yes	no	no
Equipment installers	no	yes	yes
Energy	yes	yes	yes
Neutral host	yes	yes	yes
Landlord/ building owners	yes	yes	yes

In the above table, the actors that might possibly be involved in the initial, project and maintenance stage are marked 'yes'. The above table 6 gives the overview of a scenario where MNOs collaborate with neutral hosts acting as intermediaries. Although collaboration between MNOs might be a possibility in the future, the current scenario in the Netherlands is different as stated above. For this Utrecht practical case study, the practicalities of the Netherlands telecom markets need to be taken into account.

Table 7: Actors involved in different stages in the three stages of small cell realisation for the Dutch telecom market

Actors	Initial	Project	Maintenance
Municipality	yes	yes	yes
Kadaster	yes	yes	no
National regulators	yes	no	no
EU policy makers	yes	no	no
Standardisation organisations	yes	no	no
Manufacturers	no	yes	yes
Fixed network operator	yes	yes	yes
Mobile network operator: KPN	yes	yes	yes
Mobile network operator: Odido	yes	yes	yes
Mobile network operator: Vodafone	yes	yes	yes
Consultants	yes	no	no
Equipment installers	no	yes	yes
Energy	yes	yes	yes
Landlord/ building owners	yes	yes	yes

In the above table, the actors who are expected to be actively involved in the respective stages are marked 'yes'.

Initial stage

In the initial stage, the considered actors are responsible for the orchestration of small cells. There are 12 actors in this stage who are involved in initial planning, site acquisition, and granting permissions and approvals for the Utrecht practical case study.

The actors involved (as seen in table 7) in the initial stage are considered for the Utrecht practical case study. Since it is assumed that no actor works alone, there are $(2^{12}) - (12 + 1) = 4083$ actor combinations possible.

Project stage

In the project stage, the considered actors are responsible for the rollout of small cells. This stage encompasses equipment (small cells, power supply, transport network) installation as well as testing and optimisation of the installed small cells. For the Utrecht practical case study, in this stage, there are nine actors. Similar to the initial stage, using the binomial theorem it is realised that there are $(2^{10}) - (10 + 1)$ combinations possible, which results in 1013 combinations.

Maintenance stage

In the maintenance stage, the considered actors are responsible for the operation and maintenance of small cells. In the Utrecht practical case study, nine actors in this stage are responsible for the maintenance of the small cells after the initial rollout. Similar to the project stage, using the binomial theorem it is realised that there are 502 possible actor combinations.

Even after dividing the deployment of small cells into three stages, the possible combinations of actors are extremely high, showcasing how complex this project is and the difficulty of realising small cells in the real world is going to be a very complex task with the need for lots for collaboration and cooperation. An example of actor exchange is detailed below to get a glimpse of how much cooperations between actors is required.

		Government					Household	Real Estate	Communication		Construction	Manufacturing	Energy	Professional Activities
		EU Policymakers	National Regulators	Municipality	Standardisation organisations	Kadaster	End users	Landlords	Mobile Network Operator	Fixed Network Operator	Equipment Installers	Manufacturers	Energy Companies	Consultants
Government	EU Policymakers	1	1	1	1	0	0	0	1	1	0	1	0	0
	National Regulators	1	1	1	1	0	0	0	1	1	1	0	1	1
	Municipality	1	1	1	1	1	1	1	1	1	1	1	1	1
	Standardisation organisations	1	1	1	1	0	0	0	1	1	1	1	1	1
	Kadaster	0	0	1	0	1	0	1	1	1	1	0	1	1
Household	End users	0	0	1	0	0	1	0	1	0	0	0	0	0
Real Estate	Landlords	0	0	1	0	1	0	1	1	1	1	0	1	0
Communication	Mobile Network Operator	1	1	1	1	1	1	1	1	1	1	1	1	1
	Fixed Network Operator	1	1	1	1	1	0	1	1	1	1	1	1	0
Construction	Equipment Installers	0	1	1	1	1	0	1	1	1	1	1	1	0
Manufacturing	Manufacturers	1	0	1	1	0	0	0	1	1	1	1	1	0
Energy	Energy Companies	0	1	1	1	1	0	1	1	1	1	1	1	0
Professional Activities	Consultants	0	1	1	1	1	0	0	1	0	0	0	0	1

Figure 20: Unweighted undirected adjacency matrix at actor level

An unweighted adjacency matrix shown in figure 20 indicates the possible number of relations between the actors to contribute to understanding the complexity of realising smalls from a quantitative perspective. Figure 20 shows 110 links between the actors indicating the need for cooperation and collaboration agreements between the actors to realise small cells.

Figure 21: Watts-Strogatz graph representing the unweighted undirected matrix at the actor level

Figure 21 visualises the Watts-Strogatz graph [31] created based on the unweighted undirected matrix in figure 20. The red links between actors represent those who are directly involved in the rollout as well as perform actions for the orchestration of the deployment. The black links represent information exchange between actors mainly involved in the communication of rules, regulations and policies and indirectly involved in the orchestration of the deployment process. The internal collaboration of the nodes is not included in this graph for the sake of simplicity. The 51 connections between actors from eight socioeconomic sectors, as illustrated by the Watts-Strogatz graph, provide plausible reasoning for why small cell deployment is such a complex trans-sector case.

Municipality of Utrecht as primary facilitator

To handle the complex trans-sector project of deployment of small cells, the Municipality of Utrecht is best suited to become the prime facilitator to avoid chaos in the future. The Municipality of Utrecht strongly supports good orchestration of small cells in Utrecht. Here good communication with all players is of great importance. The goal of the Municipality of Utrecht is to facilitate the rollout of small cells in the city in a way that is appropriate for the city. As seen above, with 14 actors being stakeholders in this project, the Municipality of Utrecht wants to coordinate the actions for all the actors to enable a seamless integration of small cells with the existing macro network in Utrecht without affecting the aesthetics of the city. The Municipality of Utrecht wants to timely know how the existing and future infrastructure plans can be utilised for small cells. Additionally, with the existence of three MNOs, the municipality wants to know the possibilities for placement of antennas and other related architectural elements to cause the least hindrance to the people as well as the environment of the city. As the implementation and maintenance of small cells are close to becoming a reality with the introduction of high-frequency bands, the municipality wants to set up rules and regulations that need to be followed by all MNOs and other involved actors for the installation of small cells. To realise this trans-sector project, the Municipality of Utrecht intends to ensure coordination among the eight socioeconomic sectors by laying the grounds for collaboration between them.

4.2 Outdoor scenario analysis

4.2.1 Proposed practical approach

To understand the possibilities for location and the practicalities involved in the deployment of small cells through means of visualisations, the following methodology was used.

- Initial introduction meeting with Municipality of Utrecht visionary expert to understand the issues faced by Utrecht and demarcating an area (see figure 22 within Utrecht for this research project.

Figure 22: The researched demarcated area in Utrecht for the practical case study falls under the category of 'extremely urbanised'

- Analysing the trans-sector nature of the Utrecht practical case study. Understanding the roles of multiple actors from each sector to determine which actors are needed to orchestrate the rollout as well as maintain the small cell network.
- A brainstorming session was conducted with the Municipality of Utrecht experts from different specialisations. This session provided an understanding of existing and future infrastructure in Utrecht and how they can be exploited to support the installation of small cells.
- Creating a repository for the possible locations for the RU, DU and CU followed by feasibility indications from the pros and cons list. Followed by creating a list of feasible scenarios based on the feasible RU, DU and CU locations.

- Creating a QGIS visualisation to understand the practicalities involved in the deployment of small cells in this dense urban area. Practicalities such as RU, CU and DU placement possibilities, backhaul possibilities, etc. are analysed with the help of QGIS and Google 3D Street Maps. The methodology used for the creation of the QGIS visualisations is described in Section 4.2.4.
- Meetings and interviews with researchers and experts from the Municipality of Utrecht and KPN were conducted to analyse the created visualisations, understand the feasibilities of scenarios, and reach conclusions about the Utrecht practical case study. The results from those meetings and interviews are described in Chapter 5.

4.2.2 Resources and software used

The resources and software used to analyse the Utrecht practical case study are detailed below.

QGIS

QGIS is a Geographic Information System (GIS) software that is free and open-source. QGIS supports Windows, macOS, and Linux [22]. It supports viewing, editing, printing, and analysis of geospatial data in a range of data formats. QGIS was previously also known as Quantum GIS. QGIS desktop version 3.36.2 version was used for this project to perform geographical calculations.

Excel

Microsoft Excel was used to read Excel files and comma-separated values (csv) which contain the lamp post coordinates, lighting power cabinets and camera coordinates. It was also used to create tables and perform basic calculations for cost estimations.

Python

The Python programming language was used to sort data sets as well format the data in a usable way. It was used to determine the height of all lamp posts and stored in a different column.

Geographic Data – Open Datasets

- National Georegister (NGR) The National Georegister (NGR) is the catalogue of geodatasets in the Netherlands. The datasets from NGR were used for getting a basic standard map for the Netherlands, which was used as the background for the QGIS visualisations.
- Publieke Dienstverlening Op de Kaart (PDOK) Publieke Dienstverlening Op de Kaart (PDOK) (Translation: Public Services On the Map) is a platform to access open datasets from the government with current geo-information. PDOK also manages the functionality of the NGR and the data providers are responsible for the content of their metadata that is made available in the NGR. The datasets are accessible via geo web services and available as downloads.
- Utrecht Open Data Utrecht Open data uses open data and is the platform of the Municipality of Utrecht. Open data only concerns information that is made public and is without copyrights.

4.2.3 Repository of possible installation locations

To make a repository of possible RU, DU, and CU locations, the criteria for the placement of these elements need to be understood. Based on the possible locations, a repository is created. Then the pros and cons are listed for each possible location. The pros and cons along with meetings with experts, help in streamlining the possible locations.

Criteria for placement of RUs

- Needs to be at a height of at least 2.2 meters (for E10 installation class) [23].

- Needs to blend in with the aesthetics of the city.
- Needs to be out of reach from the general public to prevent vandalism.
- Needs power network for operating.
- Needs transport network for operating.
- The volume of an RU must be smaller than 30 litres [23]. [1]
- Free line of sight is available.

1a: RUs on tall lamp posts
In the research area within the city centre, there are 718 lamp posts. Out of them, 83 lamp posts are higher than three metres. Lamp posts higher than three metres are called tall lamp posts from this point forward. In this case, it is considered that an RU will be placed on top of a tall lamp post.

Pros:

- A power network is available.
- Lamp post is a government property, so no other party permits are required during installation.
- The RU will be in an easily accessible location by engineers.

Cons:

- A transport network is required.
- Digging for the transport network is required.
- The power network for lamp posts might not be reliable enough for small cells.
- There needs to be smart integration of RUs with lamp posts, which will blend in plain sight without creating visual pollution. So it will be expensive.

1b: RUs on short lamp posts
In the research area within the city centre, there are 718 lamp posts. Out of them, there are 635 lamp posts less than the height of 3.5 metres. In this case, it is considered that an RU will be placed on top of an old-fashioned lamp post.

Pros:

- A power network is available.
- Lamp post is a government property, so no other party permits are required during installation.
- The RU will be in an easily accessible location by engineers.

Cons:

- A transport network will be required.
- Digging for the transport network is required.
- The power network for lamp posts might not be reliable enough for small cells.
- Needs smart integration of RUs with lamp posts, which will blend in plain sight without creating visual pollution. So it will be expensive.

[1] An example of an RU is the Ericsson AIR 4435. AIR 4435 is a Time Division Duplex (TDD) antenna-integrated radio unit featuring a 4T4R configuration. With a compact volume of 7 litres, a weight of 7 kilograms, and an output power of 4 × 20W, it is well-suited for 5G mid-band deployments [8].

- There are laws prohibiting the installation of other electrical equipment on these old-fashioned lamp posts.

2: RUs on security camera poles
RU is placed on a security camera pole.

Pros:

- The RU will be at a height of above three metres.
- A power network is already available.
- The RU will be at a location which can be easily accessed by engineers.

Cons:

- A transport network is required.
- There might be rules regarding installing RUs along with security cameras on the same pole.

3: RUs on bus stops:
The RU will be placed on top of a bus stop.

Pros:

- Power network is available.
- In government property, no third-party permits are required.
- Easily accessible location, so if the DU or CU needs repair, it can be easily accessed by engineers.

Cons:

- Transport network is required.
- Digging for the transport network needs to be done.
- Bus stops are not above three meters in height, so there are possibilities of vandalism.
- It is hard to place a RU which will blend in plain sight without creating visual pollution.
- Currently the presence of green plants on top of bus stops will make it hard for placement of RUs.
- In four years, the bus stops will be renovated so it is not feasible in the short term.

4: RUs on building facades:
RUs are placed on the facades of the building.

Pros:

- Can be at a height above three meters which will be a safe location as well as provide the required free line of sight.

Cons:

- A transport network is required.
- A power network is required.

- Needs seamless integration of RUs with the facade of the building, which will blend in plain sight without creating visual pollution. So it will be expensive.

5: RUs on existing macro cell base stations:
RUs are installed in the existing macro cell base station.

Pros:

- Since the base stations are already situated in a safe and secure location, collocating the DU and the CU in the KPN base station is a safe choice.
- A transport network is already available.
- A power network is already available.
- Maintenance is easier because the location is easily accessible by MNOs and municipalities.

Cons:

- Frequency interference with the KPN base station is a possibility and will need careful planning.
- Small cells need to offer capacity at the street level. Therefore installing RUs on tall buildings with macro cell base stations might make small cells lose their value.
- Permission from the building owner will be required.

Criteria for placement of DUs and CUs:

- Needs to be out of reach from the general public to prevent vandalism. Therefore needs to be in a secure location.
- Needs a power network for operating.
- Needs transport network for operating.

6: DU and CU in existing macro cell base stations:
DU and CU are installed in the existing macro cell base station.

Pros:

- Since the base stations are already situated in a safe and secure location, collocating the DU and the CU in the KPN base station is a safe choice.
- A transport network is already available.
- A power network is already available.
- Maintenance is easier because the location is easily accessible by MNOs and municipalities.

Cons:

- Frequency interference with the KPN base station is a possibility and will need careful planning.
- Capacity of the base station backhaul needs to be assessed to check if it can reused for small cells.
- It needs to be checked if permission from the building owner is required.

7: DU and CU collocated in wharf cellars:
The DU and the CU will be collocated at a wharf cellar which is already used by the energy company (Stedin) for its equipment.

Pros:

- DU and CU will be in a safe and secure location.
- A power network is already available.
- Easily accessible by engineers for maintenance.

Cons:

- Transport network needs to be made available.
- Digging for the transport network needs to be done.
- MNOs and energy companies need to collaborate to share infrastructure.

8: DU and CU situated in heritage site:
The DU and CU are placed inside a heritage site.

Pros:

- Power network is already available.
- DU and CU will be in a safe and secure location.

Cons:

- Transport network needs to be made available.
- Heritage Site Conservationists need to agree to collaborate.
- DU and CU need to be away from visitors.
- Should not affect the aesthetics of the site by any means
- Maintenance will be difficult, as permission will be required from the party who takes care of the heritage site.

9: DU and CU in Albert Heijn:
The DU and CU will be placed inside Albert Heijn. In this scenario, Albert Heijn is taken as an example. It can be any chain department store, which is located in different locations throughout the Netherlands.

Pros:

- Can use the power network of the property.
- Can use the transport network of the property.

Cons:

- The municipality and MNO need to come to an agreement with the property owner for using space, power and transport network of the property.
- Not an easily accessible location. If the CU and DU need repair, the owner of the property needs to give access to the engineers.

- If the owner of the property owner wants to make renovations on the property, the owner needs to consult with the MNOs regarding the location of CU and DU. This will be inconvenient for the property owner.

Table 8: Feasibility of possible installation locations for RU, DU and CU

	Installation location possibility	**Environment**	**RU feasibility**	**DU and CU feasibility**
1a	tall lamp post	outdoor	possible	likely impossible
1b	short lamp post	outdoor	impossible	impossible
2	security camera pole	outdoor	likely impossible	impossible
3	bus stop	outdoor	impossible	impossible
4	facade/gable	outdoor	likely possible	impossible
5	macro cell base station	outdoor	likely possible	possible
6	wharf cellar	indoor	impossible	likely possible
7	heritage site	indoor	impossible	likely impossible
8	venues such as Albert Heijn	indoor	impossible	likely impossible

Table 8 categorises the installation locations into the 'possible', 'likely possible', 'likely impossible' and 'impossible' categories based on the pros and cons. All the indoor locations are deemed impossible for RUs as this table focuses on outdoor small cells. The locations deemed impossible are left out in the list of scenarios shown in Table 10.

Table 9: Feasibility of possible installation scenarios

Scenario	**Feasible RU locations**	**Feasible DU and CU locations**	**Combined Feasibility**	**Remark**
1.1	RU on tall lamp post	DU and CU in wharf cellar	likely possible	For placement of antennas higher than five metres, permission from the municipality is required.
1.2	RU on tall lamp post	DU and CU on a macro cell base station	possible	For placement of antennas higher than five metres, permission from the municipality is required.
2.1	RU on security camera pole	DU and CU in a wharf cellar	likely impossible	Combining small cells with a security camera could be forbidden due to current municipal security policy.
2.2	RU on security camera pole	DU and CU in a macro cell base station	likely impossible	Combining small cells with a security camera could be forbidden due to current municipal security policy.
3.1	RU on facade/gable	DU and CU in a wharf cellar	likely possible	Permissions from property owners will be necessary.
3.2	RU on facade/gable	DU and CU in a macro cell base station	likely possible	Permissions from property owners will be necessary.

Table 9 shows the possible scenarios created by placing the RU, DU and CU in 'possible', 'likely possible' and 'likely impossible' locations (as shown in table 8). These scenarios were further analysed with the help of the Municipality of Utrecht and KPN experts. Based on interviews, it was decided that scenarios 1.1, 1.2, 2.1 and 2.2 need to be taken into consideration for visualisations using QGIS. Security camera poles are situated in busy areas, where extra capacity might be required. An agreement needs to be reached within departments of the municipality if security camera poles can be utilised for RU installations. For this thesis, it is assumed that security camera poles can be utilised, therefore scenarios 2.1 and 2.2 are considered for further analysis.

4.2.4 QGIS visualisation methodology

QGIS is used for visualising and processing the sensor datasets and other geographical entities (such as the lamppost objects, the buildings of the public space, the road infrastructure, etc). QGIS accepts coordinate files as input and places points (or other geometries, such as polygons for buildings and lines for roads) on the map, in a visually dynamic context. In this master thesis, the shortest distance from the RU to the DU and CU locations is calculated and displayed using various tools available in QGIS.

Methodology

An area was demarcated in the area of Utrecht with the help of the representative of Municipality of Utrecht for this research. This area will be addressed as the research area from now on. To understand the practicalities involved in the deployment of small cells in this dense urban area, five areas were selected for the installation of RUs.

Figure 23: Lamp posts higher than three metres

In QGIS, all the lamp posts within the researched area were plotted. The lamp posts higher than three metres were extracted using Excel and are visualised in Figure 23. It can be seen that the street surrounding the canal, known as Oudegracht, has barely any lamp posts higher than three meters. It can be concluded that installing RUs on tall lamp posts is not a solution in that area. So security camera poles or facades of buildings need to be taken into consideration for the Oudegracht area.
The locations for RU were recommended based on:

- availability of a pole (ex: security camera pole) or tall lamp posts
- least clutter around the antenna
- interview with Municipality of Utrecht experts

A radio unit needs to be in a position with the least clutter around it to ensure optimal signal propagation and minimise interference. Clutter, such as buildings, trees, and other obstructions, can block or scatter radio signals, reducing coverage, signal strength, and quality. To assess the availability of unobstructed space for small cells, a calculation of 'free space' around the RU is done. Free space indicates the area (radius of 10 metres) around the RU free from obstacles such as buildings. The following steps are taken using Excel and QGIS to check the availability of free space :

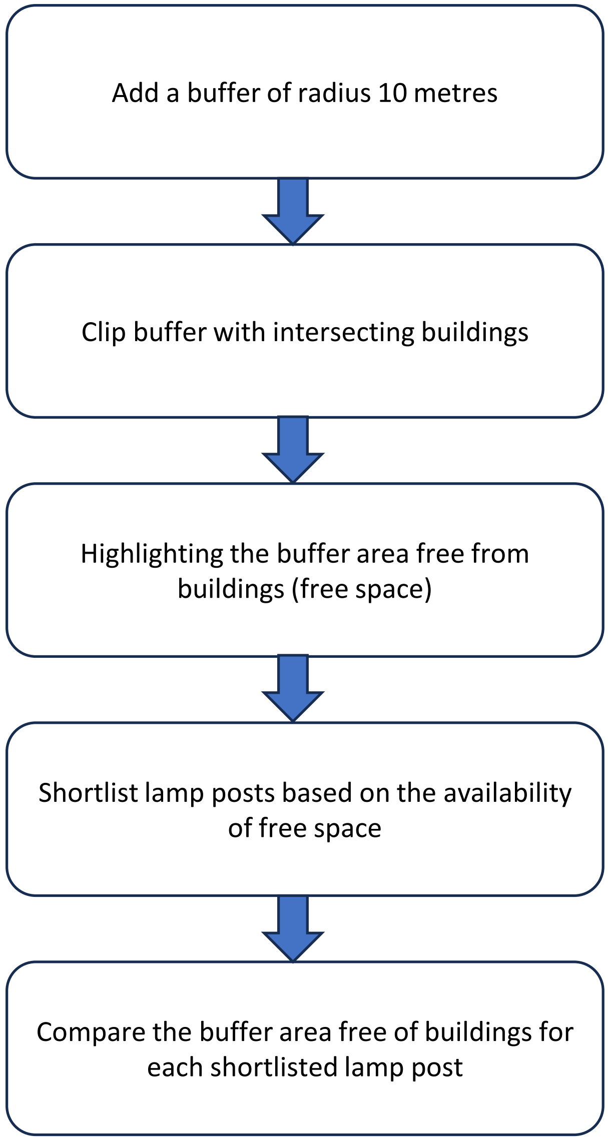

Figure 24: Flowchart for determining free space

An example of how the methodology shown in figure 24 is followed is shown in appendices E and F.

Figure 25: Tall lamp posts buffer with available free space

Figure 25 visualises all the lamp posts and their respective available free space within a radius of 10 metres.

Figure 26: Three clusters of tall lamp posts in the researched area

Figure 26 visualises the finding of three tall lamp post clusters from visual inspection using QGIS. These three clusters are referred to in this research as:

- Catherijnesingel cluster
- Stadhuisbrug cluster
- Neude cluster

For each cluster, the tall lamp posts with the most free space around them are looked into in more detail with the help of Google 3D street view maps. The RU location for each of these clusters is mentioned in Chapter 5. The three recommended locations for RU placement were discussed with a Municipality of

Utrecht expert. Upon following the advice from the expert, two more RU placement locations are proposed near the Oudegracht area (discussed in Chapter 5, section 5.1). Five locations for RU placement are proposed in this thesis.
Based on table 9 and interviews from experts, it is realised that a macro cell base station and Stedin-owned/hired wharf cellar are the two possible locations for installing the DU and CU. A Stedin-owned/hired wharf cellar and KPN macro cell base station are proposed based on their proximity to the five recommended RU locations. Two visualisations are created in QGIS by connecting the five RUs to DU and CU situated in a Stedin-owned/hired wharf cellar and KPN macro cell base station respectively.
The cost estimation for the Utrecht practical case study is performed similarly to the financial analysis done in Chapter 3, section 3.2.

Figure 27: Shortest path from a RU to Stedin-owned/hired wharf cellar

Figure 27 shows the shortest path from a proposed RU location to the Stedin-owned/hired wharf cellar. The shortest path is created using the QGIS tools as well as manually by following the path geometry obtained from the NGR database. This contributes to the understanding of where digging needs to be done for fibre fronthaul connection, assuming that there are no free cables available underground at these locations presently. To estimate the total cost of digging, the shortest path from all five recommended RU locations to the Stedin-owned/hired wharf cellar and KPN macro cell base station are plotted. The results are analysed in Chapter 5, section 5.1.

4.3 Indoor scenario analysis

Indoor analysis for small cells is different from that of outdoor. The challenges that need to be considered for small cells are mentioned in the following section.

4.3.1 Challenges faced by an indoor cellular network:

Exhaustion of lower operating frequencies: Lower frequencies, which offer better range and building penetration, have become fully utilized. Higher frequencies, now being deployed, have less penetration capability. The highest frequencies used by 5G are particularly limited in both range and penetration [11].

Changes in building materials: Modern buildings use eco-friendly materials like low-emissivity (Low-E) glass, which reflects infrared radiation to maintain temperature but also reflects cellular signals, reducing outdoor-to-indoor penetration. Additionally, soundproof glass and walls, designed to reduce noise, further attenuate radio waves, impeding signal propagation inside buildings [11].

Increased demand for mobile services: The growing demand for mobile services pressures Mobile Network Operators (MNOs) to densify their networks with more sites and increased spectrum deployment. This requires additional equipment and permissions from planning authorities and site landlords, along with increased rent, making it challenging to meet the demand. Localized congestion can occur when the network cannot keep pace, leading to suboptimal service even when it is available [11].

Expectation of ubiquitous service: Users now expect cellular service in all locations, including difficult-to-cover indoor areas such as underground spaces, parking lots, and basements. This expectation places additional pressure on MNOs to eliminate 'not-spots' and ensure consistent indoor coverage [11].

Therefore relying on MNOs to provide indoor coverage everywhere is impractical. The property owner needs to come to an agreement with the MNOs to provide capacity and coverage to the users inside the property. There are quite a few ways to provide indoor coverage such as WiFi, Distributed Antenna Systems (DAS), etc [11]. In this thesis, neutral-hosted small cell networks and private networks will be discussed in detail from the perspective of the actors. One way of providing indoor coverage is by facilitating a private network. This is done by building owners or enterprise owners facilitating a private network by forming an agreement with the MNO. In the Netherlands, KPN implements a private network in two ways:

- The radio network and the private core network are built by the MNO
- The existing radio network of the enterprise (a distributed antenna system installation in the present situation) is connected to a private core, built by the MNO

Although the maintenance is the responsibility of the building/enterprise owner, configuring and managing requires telecom expertise. Therefore the responsibility for maintenance is delegated to the MNO. Hence in the future, it is a possibility when a private indoor small cell network is deployed, it will be maintained by the MNO.

To take advantage of the flexibilities offered by 5G, an indoor small cell private network can be considered a feasible solution. MNOs and enterprise/building owners can utilise small cells to provide capacity and coverage to users inside a property and it is less expensive than DAS [1]. To facilitate a private indoor small cell network, a neutral host can act as an intermediary between the MNOs and property owners. The role of neutral hosts is discussed in the following section.

4.3.2 Neutral hosts

A neutral host is a commercial entity that provides a single, shared network solution on an open-access basis to one or more MNOs. Neutral hosts invest in the long term and act as intermediaries between end-customer landlords or tenants and the MNOs, providing the commercial relationship and the technical expertise to deploy systems using licensed spectrum. In some cases, the neutral host will fully manage this deployment on behalf of the MNO [1]. The main functions of a neutral host are:

- Site Acquisition and Construction: Neutral hosts acquire and develop various types of sites, either proactively or based on orders from an MNO. This can include structural construction, fibre installation, edge data centres, etc [1].
- Infrastructure Management: In the case of a private network in a rented building, neutral hosts manage, operate, and maintain the infrastructure on behalf of tenants. Tenants pay rent and fees based on the services provided, which may be defined by factors such as area coverage, user experience, service

availability, and data traffic volumes. Management duties include alarm monitoring, fault maintenance, performance management, capacity planning, configuration, accounting, and security [1].

- Service Provision: Neutral hosts offer various services, including but not limited to negotiating contracts with site owners and freeholders, providing installation, maintenance, and management services for sites, facilitating site access for MNO staff, etc [1].

Benefits for MNOs

Optimized network expansion: Neutral hosts provide an attractive solution for extending networks in areas with poor coverage or insufficient capacity – a solution that optimizes operating costs and reduces capital expenditure [1].

Long-term investment value: Neutral host technology is upgradeable and scalable to meet future demands [1].

Traffic offload: Local spectrum licenses applied to neutral host networks mean MNOs can offload data traffic and users from their networks to nearby private neutral host networks. This enhances customer quality of service. MNOs can also leverage the shared infrastructure of venue owners. That cuts costs and operational burdens and allows for more efficient network management and resource allocation [1].

Easing deployment constraints: Local rules sometimes limit the installation of infrastructure in crowded areas or protected sites. Shared infrastructure means all providers can cover these areas without having to struggle for access [1].

Benefits for governments, municipalities and policymakers

Digital Inclusion: Shared infrastructure is a cost-effective solution for providing coverage in underserved areas, ensuring equal access to essential services even in remote regions [1].

Economic Growth: Neutral host makes network densification more affordable and logistically simpler. This leads to improved cellular service provision, enhanced business efficiency, and supports remote working, the digital economy, and innovation. Additionally, it facilitates the integration of IoT devices in manufacturing, boosting remote monitoring, supply chains, and flexible manufacturing practices, thereby accelerating economic growth [1].

Simplified Solutions: Utilising shared infrastructure reduces the number of site applications, speeds up approvals, and improves coordination with regulatory bodies. This approach minimizes street clutter, lowers deployment costs, and simplifies maintenance, resulting in more mobile services for citizens [1].

Efficient Spectrum Usage: Neutral hosts promote optimal spectrum usage by supporting multiple market players and ensuring fair access to spectrum resources. This fosters a competitive market environment and aligns with regulatory goals [1].

Example of infrastructure sharing in Italy

A recent example of infrastructure sharing is seen in Italy. Tim and Vodafone, the two main telecom operators in Italy, collaborated to share the DAS system built by INWIT to provide fast and stable internet to travellers from Milan to San Babila, through Milan's M4 underground line [19]. In this scenario, INWIT acts as the neutral host. This collaboration underlines the importance of infrastructure sharing to accelerate the development of telecommunications networks. It can be concluded that neutral hosts are integral in deploying small cells as multi-operator solutions.

Current situation in the Netherlands

The Dutch telecom market is highly competitive, and while there is potential for infrastructure sharing, the role of neutral hosts remains limited. MNOs are open to collaboration, such as deploying small cells together, but generally resist the idea of neutral hosts selling capacity to them, as they do not intend to support a neutral host monopoly. Based on expert interviews, it is realised that MNOs do not find it necessary to cooperate with neutral hosts in the Dutch telecom market at this moment. Currently, network sharing is primarily passive, with MNOs sharing infrastructure like tower locations or power. Therefore for the municipality of Utrecht, the rollout of small cells results in the installation of a significant amount of equipment, excessive use of public sites (e.g. light poles) and ground and cable work. There is a risk that the three operators may deploy overlapping networks, resulting in a combined capacity that exceeds the demand. However, there is potential for active network sharing in the future, where MNOs could share base station equipment, with one operator managing the installation at a given location. An example of this cooperation can be seen in private networks, where MNOs, such as in large buildings in Amsterdam, share infrastructure by consolidating their equipment and using a single connection to the antenna. This approach could also be extended to small cell deployments in the future.

Furthermore, it is estimated that hyperdense areas will require more than 150 small cells per square kilometre to meet capacity needs [26]. If each of the three MNOs were to install separate antennas to meet this demand, it would result in at least 450 antennas per square kilometre, leading to significant visual pollution—an outcome the municipality seeks to avoid. This is why active sharing of equipment will be important. Therefore the MNOs need to be prepared for the active sharing of equipment to realise small cells.

4.4 Summary

Section 4.1 describes the problems faced by the Municipality of Utrecht that might hinder the deployment of small cells. Section 4.2 shows the complexity of the trans-sector nature of the deployment of small cells by means of visualisations and matrices. In the Utrecht practical case study, it was taken into consideration that the three MNOs (KPN, Odido and Vodafone) do not actively share infrastructure and the MNOs do not find it necessary to cooperate with neutral hosts in the Dutch telecom market at this moment. The lack of active sharing presents a real challenge for the municipality, as hyperdense areas are estimated to require around 150 small cells per square kilometre. Separate installations by each MNO could result in approximately 450 antennas per square kilometre, leading to significant visual pollution—an outcome the municipality seeks to avoid. As for the fixed network operator, KPN still is currently the main fixed network operator in the Netherlands. Therefore when calculating the possible combinations, the number of MNOs was counted as three, the number of fixed network operators was considered one and the neutral host actor was not considered. This resulted in 14 actors, resulting in approximately 8178 possible actor combinations, indicating the need for extensive orchestration and collaboration. Section 4.2 section answers SQ3.1. Additionally, Section 4.2 lists all the pros and cons for possible installation locations of RUs, DUs and CUs and evaluates the feasibility of installation scenarios based on expert interviews, QGIS visualisations and Google Maps.

The indoor scenario analysis from the perspective of actors was described in section 4.3. Section 4.3 summarises the role of the neutral host, illustrating how the neutral host model provides significant benefits to multiple actors. An example of collaboration between Mobile Network Operators (MNOs) and a neutral host was provided to highlight the advantages of infrastructure sharing. However, based on insights gathered from expert interviews, it was concluded that MNOs in the Dutch telecom market currently do not find cooperation with neutral hosts necessary at this moment.

Chapter 5

Results from the Utrecht practical case study

This chapter presents the possible placement locations for RU, DU and CU. The possible placement locations are determined using QGIS visualisations and interviews with the Municipality of Utrecht and KPN experts. Based on these interviews, this chapter gives an overview of other practicalities that can promote or hinder the deployment of small cells in the future.

5.1 Results from QGIS visualisations

This section proposes the five RU possible locations in the research area as well as two DU and CU locations. Initially, three locations are proposed for RU placements in each cluster shown in 26. Following a meeting with experts from the Municipality of Utrecht, two more locations are proposed for RU. A financial analysis based on QGIS visualisations is also discussed.

Catherijnesingel cluster

From the Utrecht expert interview, the Catherijnesingel area is identified as one of the most crowded regions within the researched area. By using the QGIS tools mentioned in Chapter 4, and upon further inspection with the help of Luchtphoto (aerial image), Google 3D street view map and site visits a tall lamp on Vredenburgplein is proposed as a suitable location for RU installation.

Figure 28: Proposed tall lamp post on Vredenburgplein for RU placement at the Catherijnesingel cluster

Figure 28 visualises the tall lamp post on Vredenburgplein for the Catherijnesingel cluster and is short-listed as one of the preferred locations for RU.

Stadhuisbrug cluster

Upon visiting the site of the Stadhuisbrug cluster, it was realised that no tall lamp posts fulfil the criteria for the placement of an RU. On visiting the research area, a security camera pole was located at the centre of the Stadhuisbrug cluster, on the Korte Minrebroederstraat. Therefore a security camera pole is proposed as a possible location for RU placement. However, it will be difficult to place RUs on security camera poles since an agreement needs to be reached within the departments of the Municipality of Utrecht.

Figure 29: Proposed security camera pole on Korte Minrebroederstraat for RU placement at the Stadhuisbrug cluster

Figure 29 shows the recommended security camera pole on Korte Minrebroederstraat for the Stadhuisbrug cluster.

Neude Cluster

Neude is an open area and there is more than one lamp post with 100% free space available around it. In a previous research internship conducted at TU Delft [17], focusing on Utrecht, a specific lamp post was identified as suitable for installing a camera. With the researcher's permission, their findings have been incorporated into this project. The tall lamp post identified for the camera installation has also been deemed suitable for RU installation. This suitability was further verified using Google Street Maps, confirming its potential for use in this thesis project. However, an agreement needs to be reached within the departments of the Municipality of Utrecht for RU placement.

Figure 30: Proposed tall lamp post for RU placement at the Neude cluster

Figure 30 shows the recommended tall lamp post proposed for the Neude cluster. The three recommended locations for RU placement were discussed with Municipality of Utrecht experts. It was advised that the Oudegracht area which is a densely populated area is challenging and will require extra capacity in the future. Following this meeting, two more locations for RU placement were recommended. As mentioned earlier, there are no suitable tall lamp posts around Oudegracht within the research area. Therefore by visiting the research area and using Google 3D street maps the following locations are proposed for RU placement.

Figure 31: Proposed tall lamp post for RU placement at Viebrug

While exploring near the Oudegracht area using Google 3D Street View Map, the lamp post shown in figure 31 was noted. This lamp post was not mentioned in the public lamp post dataset obtained from Utrecht Open Data. Upon visiting the location of this lamp post, it is realised that this tall lamp post fits the criteria for RU placement and is proposed as a possible location for installing an RU. However, this lamp post is situated on a busy street, so there is a risk of collisions and preventive guidelines need to be discussed before installation. Furthermore, while looking into architectural elements near Oudegracht using Google 3D Street View Map, a security camera pole was located near Bakkerbrug Street. Using QGIS tools and upon visiting the research area it is realised that this security camera pole is suitable for RU placement.

Figure 32: Proposed security camera pole for RU placement at Bakkerbrug

Figure 32 visualises the proposed lamp post for Bakkerbrug Street. The security camera pole is owned by the Municipality of Utrecht, so there is a possibility that this pole can be used for the installation of RUs. However, an agreement needs to be reached with the department responsible for security cameras before installing an RU.

Figure 33: Five proposed locations for RU placement

Finally, all five proposed possible locations for RU placement are shown in figure 33 using the methodology described in Chapter 4, section 4.3. The locations are:

- Vredenburgplein: tall lamp post
- Bakkerbrug: security camera pole
- Viebrug: tall lamp post
- Korte Minrebroederstraat: security camera pole
- Neude: tall lamp post

Based on the pros and cons list, meetings and interviews with experts, rules and regulations and table 8the recommended locations for DU and CU are:

- wharf cellars owned/hired by Stedin
- existing KPN macro cell station

Figure 34: MNO base stations and Stedin wharf cellars

The above figure 34 shows all the base stations and wharf cellars in the research area. The wharf cellars observed here are owned/hired by Stedin to place their lighting power cabinets and other equipment. Out of these wharf cellars and base stations, one single wharf cellar and KPN base station were preferred to place the DU and CU.

Figure 35: Selected KPN macro cell base station and Stedin wharf cellar

Figure 35 depicts the preferred KPN base station (highlighted in a red circle) and a Stedin-owned/hired wharf cellar (highlighted in a blue circle). The recommendations were made based on which KPN base station and wharf cellar would be closest to the five recommended locations for the installation of RUs.
In QGIS, there are two scenarios created by connecting the five RUs to the DU and CU in the wharf cellar and KPN base station respectively. Both the scenarios grouped will now be referred to as QGIS scenarios from this point forward.

Wharf cellar scenario

The RUs were placed in the five proposed locations. The RUs were then connected to the DU and CU situated in a Stedin-owned/hired wharf cellar. The shortest distance was plotted from the wharf cellar to RU locations to estimate the cost of digging. From here onwards, this scenario is called the wharf cellar scenario.

Figure 36: Five RUs connected to DU and CU located in the Stedin-owned/hired wharf cellar

Cost Calculation for wharf cellar scenario

The shortest paths from the Stedin managed wharf cellar to the five proposed RU locations are shown in figure 36. To understand the monetary investment for the installation of small cells in terms of money, the factors considered are:

- Digging: It is the most expensive factor for the installation of small cells that needs to be kept in mind
- Small Cell Equipment: RU, DU, CU
- Equipment to support the installation of small cell: fibre/ethernet, cable or PoE

Table 10: Cost estimation for placing a RU at Bakkerbrug connected to the DU at the Stadhuisbrug wharf cellar

RU location: security camera pole	**DU and CU location: wharf cellar**	**Distance (m)**	
136448.757, 456163.511	**136619.97, 455989.18**	**120.075**	
Bakkerbrug	**Stadhuisbrug**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	120.075	12007.5
Power/meter	0.1	120.075	12.0075
fiber/m	50	120.075	6003.75
Installation Cost			1000
Backhaul			32000
Total			**≈63520**

Table 11: Cost estimation for placing a RU at Viebrug connected to the DU at the Stadhuisbrug wharf cellar

RU location: tall lamp post	**DU and CU location: wharf cellar**	**Distance (m)**	
136448.757, 456163.511	**136619.97, 455989.18**	**225.166**	
Viebrug	**Stadhuisbrug**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	225.166	22516.6
Power/meter	0.1	225.166	22.5166
fiber/m	50	225.166	11258.3
Installation Cost			1000
Backhaul			32000
Total			**≈79300**

The above tables 10 and 11 give a cost estimate for placing an RU at Bakkerbrug and Viebrug respectively and then connecting the RUs to a DU and CU in the Stedin-owned/hired wharf cellar. The considered costs for each parameter are based on expert interviews. This financial analysis is done for each of the five RU proposed RU locations.

At the Bakkerbrug and Viebrug locations, the costs associated with fibre installation and digging account for approximately 30% and 40% of the total estimated deployment costs, respectively. Therefore the implementation of wireless fronthaul [27] offers a substantial opportunity to reduce these costs.

Table 12: Cost for installing DU and CU in the Stedin-owned/hired wharf cellar

Location of RU	**Location of DU and CU (wharf cellar)**	**Distance**	**Cost(€)**
Vredenburgplein	Stadhuisbrug	356.61	99030
Bakkerbrug	Stadhuisbrug	120.075	63520
Viebrug	Stadhuisbrug	225.166	79300
Korte Minrebroederstraat	Stadhuisbrug	110.32	62060
Neude	Stadhuisbrug	254.481	83700

Table 12 shows the cost estimations for all the five proposed locations for placement which are connected by a fibre to the proposed DU and CU location in the Stedin-owned/hired wharf cellar. This financial analysis assumes that there are no readily available fibre connections in the five proposed RU locations. It is observed from the above table that digging is the most expensive factor in the cost estimations.

KPN base station scenario

The RUs were placed in the five proposed locations. The RUs were then connected to the DU and CU situated in a KPN base station. The shortest distance was plotted from the base station to RU locations to estimate the cost of digging. From here onwards, this scenario will be called the KPN base station scenario.

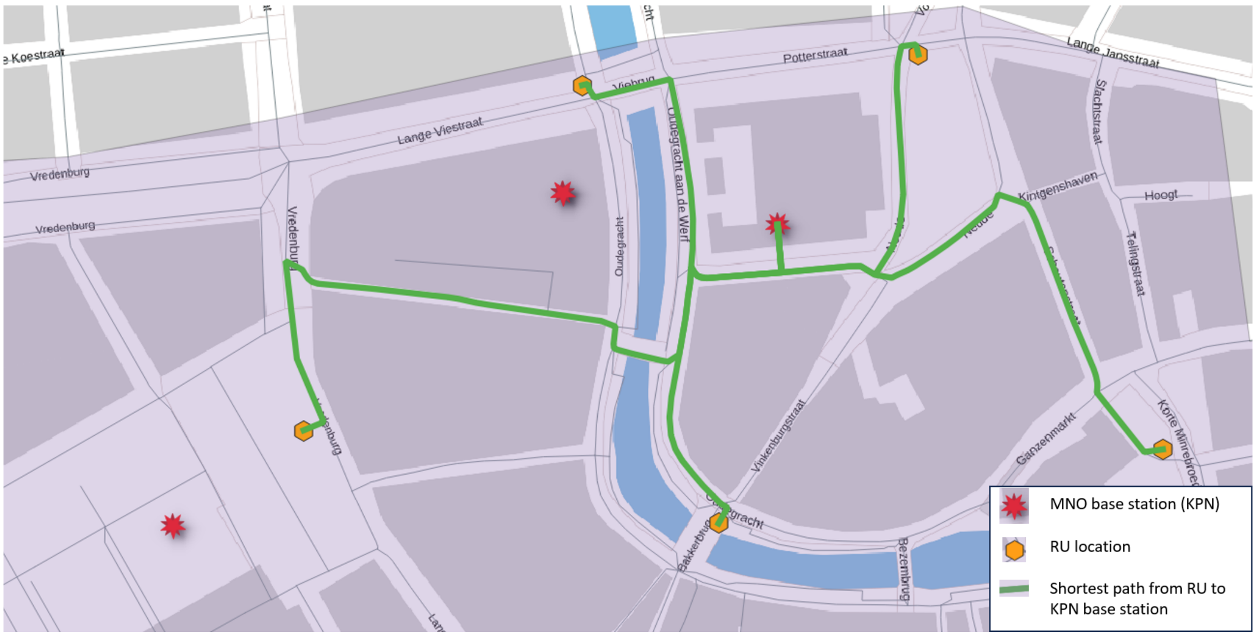

Figure 37: Five RUs connected to DU and CU at the KPN base station

Cost Calculation for KPN base station scenario

The shortest paths from the Stedin-managed wharf cellar to the five proposed RU locations are shown in figure 37. To understand the monetary investment for the installation of small cells, a few factors were considered:

- Digging: It is the most expensive factor for the installation of small cells that needs to be kept in mind
- Small Cell Equipment: RU, DU, CU
- Equipment to support the installation of small cell: fiber/ethernet, cable or PoE

Table 13: Cost estimation for placing a RU at Bakkerbrug connected to the DU at the Neude KPN base station

RU location: security camera pole	**DU and CU location: KPN base station**	**Distance (m)**	
136448.757, 456163.511	**136528, 456107**	**146.868**	
Bakkerbrug	**Neude**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	146.868	14686.8
Power/meter	0.1	146.868	14.868
fiber/m	50	146.868	7343.442
Installation Cost			1000
Backhaul			32000
Total			**≈67550**

Table 14: Cost estimation for placing a RU at Viebrug connected to the DU at the Neude KPN base station

RU location: tall lamp post	**DU and CU location KPN base station**	**Distance (m)**	
136448.757, 456163.511	**136528, 456107**	**153.532**	
Viebrug	**Neude**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	153.532	15353.2
Power/meter	0.1	153.532	15.35
fiber/m	50	153.532	7676.61
Installation Cost			1000
Backhaul			32000
Total			**≈68550**

The above tables 13 and 14 give a cost estimate for placing an RU at Bakkerbrug and Viebrug respectively and then connecting the RUs to the proposed DU and CU location in the KPN macro cell base station. The considered costs for each parameter are based on expert interviews. For the Bakkerbrug and Viebrug locations, the cost of fibre installation and digging constitutes approximately 30% of the estimated total deployment costs. Therefore, the implementation of a wireless fronthaul architecture [27] presents a significant opportunity for cost reduction. Additionally, by collocating DU and CU within an existing macro cell base station, MNOs must ensure that the backhaul capacity of the macro cell is sufficient to support the associated small cells. If verified, this approach could reduce total deployment costs by 80%.

Table 15: Cost for installing DU and CU in the KPN base station

Location	**Location of DU and CU (KPN base station)**	**Distance**	**Cost(€)**
Vredenburgplein	Neude	345.87	97410
Bakkerbrug	Neude	146.868	67550
Viebrug	Neude	153.532	68550
Korte Minrebroederstraat	Neude	226.734	79530
Neude	Neude	140.504	66590

Table 15 shows the cost estimations for all the five proposed locations for placement which are connected by a fibre to the proposed DU and CU location in the KPN macro cell base station. This financial analysis assumes that there are no readily available fibre connections in the five proposed RU locations. It is observed from the above table that digging is the most expensive factor in the cost estimations. In both QGIS scenarios, several key considerations emerged. First, two proposed locations for RUs are on security camera poles, which are typically owned by the municipality. Given that the municipality's security department might object to the installation of RUs by an MNO, the feasibility of using these poles for small cell deployment needs to be thoroughly discussed within the municipal administration. Additionally, digging along the shortest paths in both scenarios should be assessed by experts, particularly as stone bridges across the canal may restrict excavation. Alternatively, laying cables visibly across these bridges could compromise the aesthetics of the area. In the wharf cellar scenario, a meeting with representatives from Stedin would be essential to explore options for shared space to house equipment. Finally, while the wireless theoretical scenario in Chapter 3, Section 3.1 discusses using solar panels and batteries to power the RUs, the practical application of solar panels may be limited due to potential visual pollution in these areas.

5.2 Interview results

5.2.1 Results from the meeting with KPN experts

From the interviews with the KPN representative, the following inferences were made:

- The wharf cellar and the base station scenario are handled as a greenfield site in QGIS. There is a possibility that fibre has already been installed in some of the locations. So digging the entire route from RU To the DU might not be necessary for all locations and might significantly reduce the cost estimations.
- For the KPN base station scenario, the backhaul of the base station can be used for the CU of the small cells. However, it needs to be verified if the existing backhaul of the base station is sufficient for the small cell backhaul.
- For this master thesis, it can be assumed that there is enough space for the placement of DU and CU along with the KPN base station equipment. Additionally, permission from the owner of the building (on which the KPN base station is located) is required for the installation of DU and CU.
- Small cells are needed to provide additional capacity to mobile networks, improve customer experience by delivering higher speeds, and achieve energy savings. Small cells operating at the 26GHz band will offer large bandwidth and thus high capacity for short radio ranges. Small cells will likely be required in hotspot locations with high traffic, such as airports, train stations, and busy city centres and offload the macro network. They could also potentially provide Fixed Wireless Access (FWA) services to shops or apartments where fibre connections are unavailable, though this scenario is less likely in most city centres.
- There is limited potential for neutral hosts in the Dutch telecom market. While MNOs can collaborate and agree on deploying small cells, they are generally not in favour of neutral hosts that attempt to sell capacity to them. MNOs do not support a neutral host monopoly. Currently, there are two ways of network sharing: active and passive. Passive network sharing involves sharing infrastructure like tower locations or power, which is common among MNOs today. However, there is potential for future active network sharing, where MNOs share base station equipment, with one MNO managing the installation at a given location.
- The Dutch mobile communication market is highly competitive and there still remains a potential for infrastructure sharing, especially for newer investments. In private networks, cooperation among Mobile Network Operators (MNOs) is already in place. For instance, in Amsterdam, within large privately owned buildings, KPN collaborates with other MNOs by placing their equipment in a single room in the basement and using one cable to connect all three sets of equipment to the antenna. One MNO is responsible for the installation. This concept could also be applied to small cell deployments.

5.2.2 Results from the meeting with Municipality of Utrecht experts

From the interview with the Municipality of Utrecht experts, the following inferences were made about the following parameters:

Recommended locations for RU: In the QGIS software five RU locations were recommended. From the interview, it was realised that other than the requirements previously mentioned for the placement of RUs in Chapter 4 section 4.2.4, other factors need to be considered when assessing the feasibility of the locations for the placement of small cells.

- Features of the Viebrug location that MNOs need to consider when installing an RU:
  1. This area is mainly occupied by bike riders. Although it is against the law, people still use their mobile devices while biking.
  2. This area is not crowded with sitting people, who usually use network services more than bikers This might change on a good weathered day (for example, a sunny summer day). So there might be a need for extra capacity on days like those.
  3. Since the recommended lamp post is tall, it needs to be made sure that it is strong and sturdy enough to tolerate heavy wind.
  4. The location for this area was recommended by analysing it on the Google 3D street view map. As the Google Maps are dated, there are no leaves on trees present in these Maps. It is mentioned by the interviewee that high-frequency waves are also affected by the presence of leaves on trees. So it is hard to predict how the coverage provided by the small cell might change when there are leaves on trees.
- Features of the Bakkerbrug location that MNOs need to consider when installing an RU:
  1. The preferred placement position for RU in the Bakkerbrug location is a security pole. So it needs to be verified if there are rules against installing other electrical equipment on a security camera pole. Since providing security to people is the most important factor and small cells interfering with the camera cannot be risked.
  2. It needs to be made sure that installing a small cell on a security camera does not affect the aesthetic of the surrounding environment.
  3. Similarly to the Viebrug situation, coverage might be affected by the leaves on trees.
- Features of the Vredenburgplein and Korte Minrebroederstraat location that MNOs need to consider when installing a small cell (RU):
  - Similar to the previous locations mentioned above, the presence of leaves on trees might affect coverage
- The location of Neude can be rejected from this list of RU locations for the following reasons:
  - The area is not busy enough location to provide extra capacity through small cells.
  - The macro grid is sufficient for providing coverage to the area.

Operation and Maintenance of Small Cells: MNOs, municipalities and building owners are all actors who need to be involved in the operation and maintenance of the small cells. The following factors need to be considered for the operation and maintenance of small cells:

- Access to Architectural Elements in Buildings: When small cell components are located within buildings, property owner permission is required for engineers to gain access. Clear protocols need to be established to ensure timely and efficient maintenance and repairs by signing agreements from the time of deployment.
- Responsibility for Pole Maintenance: Different poles come with varying regulations. In the event of damage, such as a car hitting a pole, it is crucial to determine the time frame for repairs and identify the responsible party—whether it be MNOs, the Municipality of Utrecht, security camera owners (typically municipalities), or another third party.

- Skill Requirements for Repairs: The various architectural elements of small cells require different types of skilled professionals for maintenance and repair. All stakeholders must be aware of which specialist to contact when specific components are damaged to ensure a quick and appropriate response.

Architectural elements in the research area that cannot be utilised for the installation of small cells:
Flag poles: Flag poles (see figure 38) are not strong and sturdy enough to handle the weight of an RU and there is no power network available.

Figure 38: Flag poles

Street signs: Street signs (see figure 39) are not strong and sturdy enough to handle the weight of an RU and there is no power network available.

Figure 39: Street sign

5.3 Summary

Section 5.1 presents the QGIS visualisations and proposes five possible locations for RU installation and two locations for DU and CU installation. Two scenarios were created using QGIS. In the first scenario, five RUs were connected by fibre to DU and CU in a Stedin-owned/hired wharf cellar and in the second scenario the five proposed RU locations were connected to a KPN macro cell base station. The financial analysis was done for both of these scenarios. It was realised that the cost of digging trenches for fibre is the highest contributor in the cost calculation, similar to the financial analysis for the theoretical scenarios in Chapter 3 section 3.2. For the wharf cellar scenario, 30% and 40% cost savings for Bakkerbrug and Viebrug locations respectively can be achieved by implementation of wireless fronthaul. In the base station scenario, if the wired fronthaul is replaced by a wireless connection, roughly 30% of cost savings can be achieved. Furthermore, if the existing backhaul of the macro cell base station is sufficient for small cells it can reduce the cost by approximately 80%. So it is very important to explore wireless fronthaul and backhaul options to reduce digging costs.

From the interviews and meetings with the Municipality of Utrecht and a KPN expert, it was realised that practicalities such as the presence of leaves on trees need to be considered when installing small cells in the future. To realise the QGIS scenarios in the real world collaboration between actors will be necessary. Additionally, it was determined that small cells will be integral in providing the extra capacity and offloading the macro network in certain hotspots.

Chapter 6

Conclusion and recommendations

This chapter presents this thesis' conclusions and recommendations for future research. Section 6.1 summarises the answers to the research questions and sub-questions. Section 6.2 proposes recommendations from the Utrecht practical case study as well as for the future deployment of small cells. Section 6.3 suggests recommendations for future research in aspects that deserve a more in-depth analysis.

6.1 Conclusions

This section answers the research questions by giving an overview of this research's findings and summarising the conclusions from the expert interviews. Based on the findings of the thesis, small cells are feasible when the boundary conditions are satisfied. Research question 3.3 focuses on identifying the critical boundary conditions that must be satisfied for the deployment to proceed efficiently.

1. **RQ1: Which is the optimal configuration for deployment of small cells from the perspective of cost, flexibility, customer satisfaction, and practicality point of view?**

   Answer: Split option 7.2x emerges as the optimal configuration for the deployment of small cells, especially in dense urban environments, such as the researched area in the Utrecht city centre. One of the key benefits of split option 7.2x is its ability to minimize the impact on transport bandwidth while maximizing the virtualization capabilities of the gNB Central Unit (CU) and Distributed Unit (DU). This efficiency is crucial in dense urban areas where bandwidth resources are often constrained and heavily utilized. By reducing the transport requirements, split option 7.2x ensures that existing infrastructure can be used more effectively, avoiding the need for costly upgrades.
   Cost-effective Radio Unit (RU) designs further enhance the appeal of split option 7.2x. The simpler and more affordable RUs facilitated by this split option are easier to deploy and maintain, making widespread adoption feasible. This is particularly important in urban settings where numerous small cells are required to ensure comprehensive coverage and capacity. Performance maintenance is another critical advantage of split option 7.2x. Unlike other split options that might suffer performance degradation due to the demands of ideal fronthaul, split option 7.2x maintains high performance, which is essential in high-density areas with a high concentration of users. This ensures a consistent and high-quality user experience, directly impacting customer satisfaction.
   The disaggregation of hardware and virtualization of RAN Network Functions (NFs) allows for resource pooling such as the CU and DU in a centralized pool to support multiple cell sites. This centralised approach enhances scalability and flexibility, enabling the network to adapt to varying demand patterns more efficiently. Such adaptability is crucial for optimizing resource utilization and ensuring the network can handle peak usage times without compromising performance. Furthermore, the O-RAN Alliance's definition of split option 7.2x, along with its open fronthaul through the eCPRI protocol, ensures interoperability between different vendors' equipment. This open standardization reduces the risk of vendor lock-in and promotes a more competitive and innovative market. The use of eCPRI

also increases efficiency through a packet-based fronthaul network, such as IP or Ethernet, which is a significant advantage in urban areas and in indoor environments such as factories and office blocks. Additionally, the amount of data to be transported scales with user traffic, making it a highly practical solution.
Lastly, split option 7.2x supports advanced RAN features such as massive MIMO, which is critical for enhancing capacity and coverage in dense urban locations. These advanced features ensure that the network can meet the growing demands for high-speed, reliable connectivity, further contributing to customer satisfaction.

To summarise, split option 7.2x stands out as the optimal configuration for small cell deployment due to its cost-effectiveness, flexibility, performance maintenance, and practical implementation advantages. Its ability to efficiently utilize existing infrastructure, support advanced network features, and ensure high interoperability makes it the best choice for modern urban network deployments. For the Utrecht practical case study, implementing split option 7.2x appears feasible through a two-product solution, with the potential to co-locate the DU and CU either in a wharf cellar or within an existing macro cell base station.

2. **RQ2: Regarding 5G small cell deployment, which option of split 5G RAN Architecture is optimal for which specific environment and use case?**

   Answer: In this master thesis, only the split options 2, 6, 7.2 and 8 are considered.

   - Split option 2: 3GPP recommended split option 2 for highly centralised applications such as fixed wireless access, (FWA), where cell-site coordination is not required and latency and bandwidth requirements on the transport network are relatively relaxed [23]. Additionally, it is known to be popular in North America for indoor, outdoor and private scenarios.
   - Split option 6: Since the higher layers are in the DU and CU and all the physical functions are in the RU, it is ideal for use cases where only centralised scheduling is required. It is optimal for indoor enterprise and private network environments.
   - Split option 7.2x: It is preferred for scenarios where cheap and simple RUs are required. Advantageous in outdoor dense urban areas such as smart cities city centres, stadiums and large public venues and rural small cell networks.
   - Split option 8: Is indoor enterprise as well as in 2G and 3G, where traffic rates are much lower. It is known to be popular in China.

3. **RQ3: What conclusions can be drawn about the impact, costs, and benefits of deploying small cells in the Utrecht practical case study? To solve this, the following sub-questions are identified:**

   - **SQ3.1: Which stakeholders/actors need to be involved in orchestrating the rollout of small cells?**

     Answer: The sectors and actors that need to be involved in orchestrating the rollout of small cells are:

     – Government: Municipalities, Kadaster, NRAs, EU policymakers
     – Communications: Mobile network operators, Fixed network operators
     – Real-estate: Landlords/building owners, Neutral hosts
     – Manufacturing: Telecom equipment manufacturers
     – Energy: Energy Companies
     – Households: End Users
     – Professional Activities: Consultants
     – Construction: Telecommunications Equipment Installer

The roles of each of these sectors and actors are provided in Chapter 2, section 2.4. Visualisation is provided in Chapter 4, section 4.1.

- **SQ3.2: What are the limitations and possibilities for the implementation of small cells?**

  For the Utrecht practical case study, the factors that might hinder the deployment of small cells are:

  - No space for underground cabling. With only 40 centimetres between the tarmac and wharf cellars, there is minimal space to lay underground cables.
  - Digging is difficult due to lack of space and old architecture (for example, bridges)
  - Preserving the aesthetics of a historic city centre such as Utrecht is important. Although this limits the possibilities for the placement of small cells
  - Absence of rules and regulations governing the placement of antenna and small cells

  During the thesis project, it was realised that only a few architectural elements in the researched area can be used for the placement of RU, DU and CU. For the placement of RUs, lamp posts and security camera poles owned by the Municipality of Utrecht were considered. For the placement of DU and CU, wharf cellars owned by/hired by Stedin and KPN base stations were considered.

- **SQ3.3: How will the environment, transport network, energy network, and underground cabling situation of the demarcated area be impacted?**

  Based on the findings of this thesis, small cell deployment in Utrecht is feasible under very challenging specific boundary conditions that ensure successful integration with the existing infrastructure and alignment with municipal regulations. These conditions encompass technical, regulatory, and collaborative factors, each of which plays a vital role in determining the viability of small cells within the research area.

  From the QGIS scenarios, the estimated fronthaul distance is calculated as the shortest distance between the RU and the DU and CU but this is an assumption for a greenfield site. There is a possibility that fibre is already installed in some of the locations, which can be utilised for small cells. If digging is required cooperation between municipality and MNOs will be integral for planning. Historic sites such as wharf cellars must not be damaged during the digging process. Careful planning will be required to ensure that the 40 cm of space available between the wharf cellars and the tarmac is optimally utilized for underground cabling. Additionally, the deployment process should minimize inconvenience to the residents of Utrecht by ensuring that disruptions are limited and managed efficiently.

  When DUs and CUs are placed at KPN macro cell base stations, the existing backhaul connection from the macro site can potentially be used. However, this depends on whether the existing backhaul capacity is sufficient, which must be assessed by the MNOs. For the base station scenario examined in this thesis, it is assumed that there is adequate space at the base stations for installing the DUs and CUs. This assumption must be verified during practical deployment by assessing both spatial availability and obtaining the necessary permissions from the macro cell base station's property owners. There are possibilities for wireless backhaul (for example, Integrated Access Backhaul and microwave), which can be integral in solving the underground cabling situation but that requires more in-depth analysis in the future.

  From the meetings and interviews with the experts from the Municipality of Utrecht, it was understood that there will be 6000 new transformer cabinets installed in Utrecht by Stedin (energy company). There is a possibility that the green transformer cabinets can accommodate a DU and CU but they will be too short for the placement of RU. Therefore, the energy transition (setting up of more power cabinets) will not be able to single-handedly resolve the issues hindering the deployment of small cells. Energy companies, like Stedin, often have strict regulations regarding the sharing of space for equipment with other companies. For the deployment scenario involving the wharf cellar owned by Stedin, collaboration between Mobile Network Operators (MNOs) and

Stedin is necessary to place the Distributed Units (DU) and Centralized Units (CU) alongside the existing energy equipment. This cooperation is critical to utilizing shared infrastructure effectively.
Two of the five proposed locations for small cell deployment in this study involve the use of security camera poles. As security is a priority, the Municipality of Utrecht, which owns these poles, may oppose installing Radio Units (RUs) on security camera poles. If security camera poles and building facades are deemed unsuitable, new poles must be installed for small cells. However, the installation of new poles may contribute to visual pollution, contrary to the municipality's aesthetic objectives.
Active and passive sharing [18] of infrastructure between the three MNOs can help minimize visual pollution, which is a key requirement imposed by municipalities. Active sharing, where MNOs jointly use transmission equipment such as antennas, reduces the number of installations required, while passive sharing of non-electronic infrastructure like poles and power supplies further decreases the number of physical structures. Such collaboration will be necessary during the practical deployment of small cells to comply with municipal regulations and public expectations concerning urban aesthetics.

- **SQ3.4: What is the cost estimation for the implementation of small cells in the demarcated area?**

  As observed from the QGIS scenarios, digging was the highest contributing factor to the cost followed by the RU, DU and CU costs. Currently, the MNOs are not interested in investing the amount predicted in the results chapter on small cells as the macro network is sufficient. When deploying small cells, the cost estimations will be integral for MNOs to determine if investing 70K(approx.) euros on deploying each small cell will have a valuable ROI.

- **SQ3.5: What other practical aspects affect the installation of small cells?**

  From the interview with Municipality of Utrecht experts, it was realised that propagation of high-frequency waves (for example, 26GHz) is notoriously sensitive to the surrounding environment. For example, if a person is sitting on a bench and enjoying the coverage provided by a small cell and a bus passes in front of them, there is a possibility that the signal will be blocked by the bus. Therefore, for higher frequencies, especially 26 GHz (mmWave), it is hard to predict coverage. The reflection of waves will depend on the material of the facade. MNOs will need to use specialised tools to predict the coverage provided by a 26 GHz small cell.
  Laws against smart integration of RUs on the black old-fashioned lamp posts hinder the deployment of small cells in the Oudegracht region, which is one of the busiest locations in the researched area.

6.2 Recommendations

6.2.1 Recommendation from the Utrecht practical case study

Based on answers from interviews and findings of the research the following recommendations are provided which can be useful in the future for facilitating the deployment of small cells in the researched area of Utrecht. Establish clear regulations for the placement of small cells. Unlike the established rules governing macro cell installations for telecom operators, small cell deployment in the Netherlands remains unregulated. A formalized handbook or set of guidelines is needed to provide consistency and accountability for all stakeholders involved.

Explore collaboration between Stedin, the energy grid operator, and Mobile Network Operators (MNOs) to share equipment space. Such partnerships could enhance efficiency by allowing infrastructure and space utilization to be optimized, thereby accelerating the deployment of small cells.

Explore infrastructure and site sharing to minimize resource wastage, including energy, infrastructure, and financial resources. This will help reduce visual pollution in the researched area and promote efficient use of resources. Collaboration between MNOs is vital to avoid redundant deployments while ensuring that growing connectivity needs are met.

Explore the use of security camera poles for the installation of Remote Units (RUs). The municipality of Utrecht must determine whether these poles can support small cell equipment. If they are not suitable, the installation of new poles will be necessary, though this will increase visual pollution.

Evaluate the possibility of leveraging the 'Open Dutch Fibre' rollout to install extra fibre and cables in existing ducts. This approach could reduce the need for additional digging in the future and support the scaling of fibre infrastructure to meet long-term network demands.

Finally, there is a need to update the publicly available data sets more frequently. Discrepancies between recorded data and the actual condition of infrastructure, like lamp posts and security camera poles, may lead to inefficient planning and delays.

6.2.2 Recommendations for general deployment of small cells

Based on answers from interviews and findings of the Utrecht practical case study the following recommendations are provided which can be useful in the future for facilitating the deployment of small cells throughout the Netherlands.

Promote collaboration among all stakeholders, particularly between Mobile Network Operators (MNOs), energy companies, and municipalities. These actors must work together to orchestrate the rollout, as no single entity can manage the need for additional capacity and coverage on its own. For example, to implement the wharf cellar scenario, an MNO must collaborate with an energy company to share infrastructure space, while the municipality should work with the MNO to plan the small cell network in a way that preserves the aesthetic of the location.

Clarify roles and responsibilities in this trans-sector project by formalizing agreements among all actors. Establishing clear guidelines for each phase of deployment will streamline operations and maintenance. For instance, if a pole is damaged, an agreement could specify whether the municipality, MNO, or another third party is responsible for repairs. This division of responsibilities will enable quicker, more effective responses. For example, municipalities could handle physical damage, while MNO engineers would be responsible for addressing system failures.

Encourage active sharing between KPN, Odido, and Vodafone to minimize costs and reduce visual pollution. By sharing antenna sites, the number of required poles could be significantly reduced, leading to more efficient infrastructure deployment while maintaining urban aesthetics.

6.2.3 Recommendations for future work

In future research, the following aspects can be investigated:
Develop a realistic coverage model for mmWave, as small cells will likely make use of the 26 GHz frequencies. A more in-depth analysis is needed to assess how factors such as weather conditions, leaves on trees, and water content in objects impact the propagation of mmWave.

Investigate coverage solutions for Wharf Cellars, as meetings during this project revealed that restaurants in the Wharf Cellars suffer from poor mobile coverage. An analysis of whether indoor small cell deployment can effectively address this issue would be beneficial.

Examine the operational aspects of MNOs, particularly the potential for active infrastructure sharing among competing MNOs in the Netherlands.

Evaluate wireless backhaul and fronthaul technologies as alternatives to costly digging operations, which were found to be the most expensive parameter in the Utrecht practical case study. Integrated Access and Backhaul (IAB) [7] is considered a promising option for mmWave, but further research is needed to confirm its feasibility.

Appendix A

List of figures and tables

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Appendix B

Definitions

Small cells
Small cells is an umbrella term for low-powered radio communications equipment (indoor or outdoor) that provides mobile and internet services within localized areas; typically, within a radius of ten meters to several hundred meters [10].

Open RAN
Open RAN is about disaggregated RAN functionality built using open interface specifications between elements. It can be implemented in vendor-neutral hardware and software-defined technology based on open interfaces and community-developed standards. Open interfaces include (open) Fronthaul and (open) Midhaul connecting the different parts of the RAN and (open) Backhaul between the RAN and the Core [20].

O-RAN Alliance
O-RAN Alliance is a specification group defining next-generation RAN infrastructures, empowered by principles of intelligence and openness. It is a worldwide community of around 200 mobile operators, vendors, and research & academic institutions operating in the Radio Access Network (RAN) industry. Its mission is to reshape the industry towards more intelligent, virtualised network elements, white-box hardware, and standardized and open interfaces. The term O-RAN refers to interfaces and architecture elements as specified by the O-RAN alliance [20].

Fronthaul
Fronthaul refers to the network that connects the radio unit to the distributed unit [32].

Midhaul
Midhaul refers to the link between the DU and CU [32].

Backhaul
Backhaul refers to the link between the CU and the core network [32].

Common Public Radio Interface (CPRI)
CPRI is an industry cooperation aimed at defining a publicly available specification for the key internal interface of radio base stations between the radio equipment control (REC) and the radio equipment (RE). The CPRI specification enables flexible and efficient product differentiation for radio base stations and independent technology evolution for RE and REC. The CPRI is a point-to-point interface [6].

Enhanced Common Public Radio Interface (eCPRI)
This is an evolution of CPRI, an interface that sends data from the RU to the DU [23].

Effective Isotropic Radiated Power (EIRP)
EIRP is the hypothetical power that would have to be radiated by an isotropic antenna to give the same

(”equivalent”) signal strength as the actual source antenna in the direction of the antenna’s strongest beam [28].

Appendix C

Acronyms and abbreviations

3GPP Third Generation Partnership Project

5G Fifth Generation

5GC 5G Core network

AMF Access and Mobility Management Function

BBU BaseBand Unit

CAPEX CAPital EXpenditure

CU Central Unit

CPRI Common Public Radio Interface

DARTs Dis-Aggregated RAN Transport study

DAS Distributed Antenna System

DL Downlink

DU Distributed Unit

eCPRI enhanced Common Public Radio Interface

EIRP Effective Isotropically Radiated Power

EMF Electro-Magnetic Fields

EPC Enhanced Packet Core

FAPI Functional Application Platform Interface

FR1 Frequency Range 1

FR2 Frequency Range 2

FWA Fixed Wireless Access

gNB next generation Node B

GSV Google Street View

HLS High Layer Split

INWIT INfrastrutture Wireless Italiane (ITalian term)

IoT Internet of Things

IP Internet Protocol

IQ In-phase Quadrature

KPI Key Performance Indicator

LLS Lower Layer Split

LTE Long Term Evolution

L1 Layer 1 - Physical Layer

L2 Layer 2 - Datalink Layer

L3 Layer 3 - Network Layer

MAC Medium Access Control

MCS Modulation Coding Scheme

MIMO Multiple Input Multiple Output

MNO Mobile Network Operator

MONET Mobile Telephony And Antennas

NF Network Functions

nFAPI network Functional Application Platform Interface

NG Next Generation

NGR National Georegister

NR New Radio

PDCP Packet Data Convergence Protocol

PDOK Publieke Dienstverlening Op de Kaart (Dutch term)

PDU Protocol Data Unit

PHY Physical Layer

QoS Quality of Service

RAN Radio Access Network

RE Radio Equipment

REC Radio Equipment Control

RF Radio Frequency

RLS Radio Link Control

ROI Return On Investment

RRC Radio Resource Control

RRU Remote Radio Unit

RU Radio Unit

SCF Small Cell Forum

SCN Small Cell Network

SDAP Service Data Adaptation Protocol

SINR Signal to Interference & Noise Ratio

TDD Time Division Duplex

TCO Total Cost of Ownership

UE User Equipment

UL Uplink

Appendix D

Meetings and interviews with experts

This chapter summarises the answers and discussions from interviews and brainstorming sessions with KPN and Municipality of Utrecht experts.

1. What are the issues faced by the Municipality of Utrecht for installing small cells?
   According to the municipality of Utrecht visionary expert, in contrast with regulations for telecom operators placing macro cell antennas, in the Netherlands small cell placing is currently not regulated (similar to placing energy transformer cabinets). The municipality of Utrecht lacks forecasts from telecom operators and energy companies about the expected traffic volume increase, the number of Small Cells and their powering needs. In the Utrecht city centre, the possibilities for new underground cabling and placing of required sinkable power cabinets are limited, specifically above the many ancient wharf cellars. The municipality of Utrecht wishes to timely know what is needed from collective requirements and facilitate a collective design process with the involvement of all stakeholders.

2. What are the possible places in the Utrecht city centre to install small cell equipment without damaging the aesthetics of the city or breaching security requirements (ex: lamp posts, horeca venues etc.)?
   According to the municipality of Utrecht experts, bus stops are not suitable for the installation of RUs due to the presence of green plants on roofs and planned reconstructions within the next four years. Additionally, lamp posts, particularly those that are only three meters tall, are not ideal for small cell installations as installation of electrical equipment on them is prohibited. The possibility of small cells encased in protective cases for installation on lamp posts was discussed, but this solution was not deemed feasible.
   Architectural elements such as building facades and security camera poles could potentially be used for small cell installations, provided third-party approvals are obtained. However, certain elements like flag poles and street signs were deemed unsuitable due to their light structure and inability to support small cells.
   If any architectural elements of a small cell are located within a building, access for engineers requires permission from the property owner. Furthermore, different poles have varying rules and responsibilities for repairs, particularly if a pole is damaged, requiring coordination among MNOs, the municipality, security camera owners, or other third parties. Skilled professionals are needed to handle and repair the different architectural elements. A need to identify the actors responsible for maintenance is integral.

3. How do the power grid and transmission grid look like in the centre of Utrecht and can these grids be easily used to accommodate small cell installation? How can the installation of (1000 new) power cabinets be exploited for possible small cell installation?
   Municipality of Utrecht experts mentioned that the knowledge from Stedin professionals is necessary to better understand the power grid's capabilities and potential for supporting small cell installations. The focus of Stedin and the municipality this year is on five neighbourhoods, with plans to expand to 75, driven by the need for energy transition and grid expansion. The possibility of infrastructure sharing between Stedin and MNOs was discussed but generally, energy companies are rigid about

sharing infrastructure. Therefore future meetings regarding possibilities of collaboration would be the next step. It was concluded that the energy transition alone will not be able to resolve the challenges associated with small cell deployment. It was agreed that collaboration between mobile network operators (MNOs), energy companies, and municipalities is crucial for addressing the challenges of small cell deployment. The energy transition alone will not solve the problem, and clear rules and regulations are needed for antenna setup. Moving forward, it was recommended to involve Stedin in future meetings to gain a deeper understanding of Utrecht's grid situation. Additionally, exploring the possibility of using the 'Open Dutch fibre ' rollout trenches to lay extra fibre and cables for future use was suggested as a potential solution to reduce the need for further digging.

4. What are the possibilities and difficulties of digging in the Utrecht city centre for cable ducts?
   When discussing the challenges of digging in Utrecht city centre for cable ducts with the municipality of Utrecht experts, it was suggested that existing 'Open Dutch fibre rollout' trenches could potentially be used for laying extra fibre and cables. This would minimize future digging and disruption.

5. How reliable is the Utrecht power network for the lamp posts? Can batteries be of help? Are solar panels allowed to power small cells?
   The feasibility of using solar panels to power the RUs was discussed with the municipality of Utrecht experts. It was concluded that solar panels are not allowed for small cell installations as they would negatively impact the city's aesthetics.

6. What role does the Municipality of Utrecht want to play in the small cell ecosystem?
   Municipality of Utrecht visionary expert: The municipality of Utrecht wants to facilitate a small cell network for the people of Utrecht and wants to be in close contact with the public to receive feedback.

7. What considerations need to be made for small cell placement locations in the master thesis report?
   According to the municipality of Utrecht visionary expert, wind speed becomes a significant concern if small cells are placed on lamp posts taller than 10 meters. Additionally, many lamp posts in the city centre, particularly in areas like Oudegracht, are old and of classical design, making them unsuitable for housing electrical equipment. However, a key advantage is that lamp posts are owned by the municipality, eliminating the need for third-party permissions. Neude could be removed from the potential RU locations as it is not busy enough to warrant additional capacity through small cells, with the existing macro grid deemed sufficient for the area. In Vredenburg, factors like the presence of bikes, the absence of sitting crowds, and the seasonal presence of tree leaves need to be considered when installing small cells on tall lamp posts. For Brakkerburg, the possibility of installing small cells on security camera poles must account for rules that prioritize security, aesthetic considerations, and potential interference from tree leaves.

8. Can you verify the actor connections in the unweighted adjacency matrix involving all the actors? The actor adjacency matrix was verified by the municipality of Utrecht visionary expert. Subsequently, MONET was discarded from the list of actors.

9. If security cameras are impossible, can it be assumed that the facades/gables of buildings can be used for small cells? The municipality of Utrecht visionary expert mentioned that security camera poles are owned by the municipality. It needs to be discussed within the municipality if security camera poles can be used for the installation of RUs.

10. What is the value of small cells for KPN or another MNO? Is 60K euros (approx. from my cost estimation) a feasible investment in small cells for KPN? Do you think the introduction of 26GHz will trigger the deployment of small cells? A KPN expert listed the benefits of small cells as:

    (a) to provide additional capacity
    (b) improve customer experience by providing higher speeds
    (c) energy saving by using small cells

    The amount of investment for small cells must be less than the value provided by small cells in a certain area. 26GHz specifically will not trigger the deployment of small cells. For each small cell, the investment and the value offered by small cells need to be analysed.

11. What do you think of the competition within the telecom market of the Netherlands? Do you think infrastructure sharing is a possibility in the future? Do you think the three MNOs in the Netherlands will collaborate in the near future? Do you see the potential involvement of neutral hosts in the future? According to the KPN expert, the market for mobile communication is very competitive but infrastructure sharing is still a possibility, especially in newer investments. In private networks, cooperation between MNOs is already in place. For example, in Amsterdam, in privately owned large buildings KPN collaborates with other MNOs. The equipment for each MNO is placed in the same room in the basement and one cable connects the three equipment to the antenna. One MNO is responsible for installation. The same concept can be used for small cells.
    There is not much potential for neutral hosts in the Dutch telecom market. MNOs can work together and agree on realising small cells. MNOs do not favour neutral hosts trying to sell capacity to MNOs. MNOs do not want a neutral host monopoly.
    There are two ways of network sharing; active and passive network sharing. Active network sharing involves sharing base station equipment whereas passive network sharing involves sharing a tower location or power. Currently, MNOs share networks passively. The expert envisions active network sharing in the future with MNOs in control and allowing one MNO to realise the installation in a particular place.

Appendix E

Codes implemented for the thesis

This chapter describes the codes implemented in various sections of the thesis.

Greedy algorithm for theoretical analysis

This section describes the code for the greedy algorithm which is used for the placement of RU, DU and CU in the wired and wireless Manhattan grid scenarios.

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.spatial.distance import cdist

# Full grid of RUs locations (10x10 grid)
rus = np.array([[x, y] for x in range(10) for y in range(10)])

# Number of RUs per DU and DUs per CU
rus_per_du = 5
dus_per_cu = 5

# Greedy algorithm to cluster RUs to DUs
def greedy_cluster(points, cluster_size):
    points = points.copy()
    clusters = []
    centroids = []

    while len(points) > 0:
        if len(points) < cluster_size:
            cluster = points
        else:
            distances = cdist([points[0]], points, 'euclidean')[0]
            cluster = [points[0]]
            points = np.delete(points, 0, 0)

            while len(cluster) < cluster_size and len(points) > 0:
                last_point = cluster[-1]
                distances = cdist([last_point], points, 'euclidean')[0]
                closest_idx = np.argmin(distances)
                cluster.append(points[closest_idx])
                points = np.delete(points, closest_idx, 0)

        cluster = np.array(cluster)
```

```
        centroid = np.mean(cluster, axis=0)
        clusters.append(cluster)
        centroids.append(centroid)

    return np.array(centroids), clusters

# Cluster RUs to determine DU positions
du_positions, ru_clusters = greedy_cluster(rus, rus_per_du)

# Cluster DUs to determine CU positions
cu_positions, du_clusters = greedy_cluster(du_positions, dus_per_cu)

# Print DU positions
print("DU positions:")
for du in du_positions:
    print(du)

# Print assignments of RUs to DUs
print("RU to DU assignments:")
for i, cluster in enumerate(ru_clusters):
    for ru in cluster:
        print(f"RU {ru} is assigned to DU {du_positions[i]}")

# Print CU positions
print("CU positions:")
for cu in cu_positions:
    print(cu)

# Print assignments of DUs to CUs
print("DU to CU assignments:")
for i, cluster in enumerate(du_clusters):
    for du in cluster:
        print(f"DU {du} is assigned to CU {cu_positions[i]}")

# Visualisation
plt.figure(figsize=(10, 10))
# Plot RUs
plt.scatter(rus[:, 0], rus[:, 1], c='blue', label='RUs')

# Plot DUs
plt.scatter(du_positions[:, 0], du_positions[:, 1], c='red', label='DUs', marker='x')

# Plot CUs
plt.scatter(cu_positions[:, 0], cu_positions[:, 1], c='green', label='CUs', marker='s')

# Draw lines from RUs to their assigned DUs
for i, cluster in enumerate(ru_clusters):
    for ru in cluster:
        plt.plot([ru[0], du_positions[i][0]], [ru[1], du_positions[i][1]], 'k-', lw=0.5)

# Draw lines from DUs to their assigned CUs
for i, cluster in enumerate(du_clusters):
    for du in cluster:
        plt.plot([du[0], cu_positions[i][0]], [du[1], cu_positions[i][1]], 'r-', lw=0.5)
```

```
plt.legend()
plt.title('RU, DU, and CU Placement')
plt.xlabel('X coordinate')
plt.ylabel('Y coordinate')
plt.grid(True)
plt.show()
```

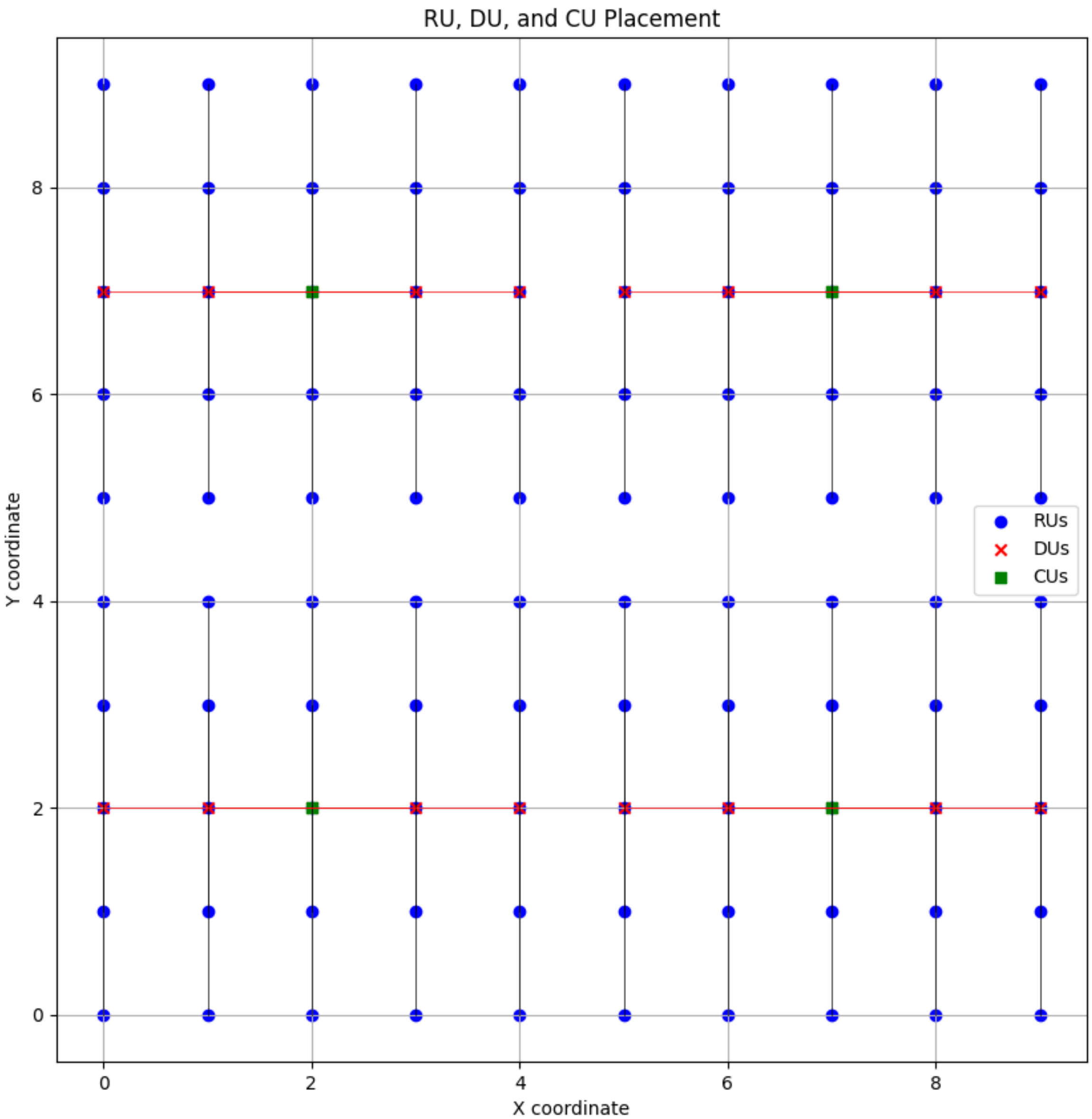

Figure 40: Greedy algorithm result

Shortlisting lamp posts and security camera poles for RU placement

This section describes the code for used for shortlisting lamp posts and security camera poles for RU placement. The shortlisted tall lamp posts and security camera poles

```
from qgis.core import QgsFeature, QgsGeometry, QgsVectorLayer, QgsProcessingFeatureSourceD
from qgis import processing

# Loading layers
lamp_posts_layer = QgsProject.instance().mapLayersByName('taller-city-lamp-posts')
buildings_layer = QgsProject.instance().mapLayersByName('research-area-buildings')

if not lamp_posts_layer or not buildings_layer:
    print("Error: One or both layers could not be found. Check layer names.")
else:
    lamp_posts_layer = lamp_posts_layer[0]
    buildings_layer = buildings_layer[0]
    print(f"Lamp posts layer found with {lamp_posts_layer.featureCount()} features")
    print(f"Buildings layer found with {buildings_layer.featureCount()} features")


    fix_geom_params = {
        'INPUT': buildings_layer,
        'OUTPUT': 'memory:fixed_buildings'
    }
    fixed_buildings = processing.run('native:fixgeometries', fix_geom_params)['OUTPUT']
    print(f"Fixed buildings layer created with {fixed_buildings.featureCount()} features")

    # Creating an output layer to store the filtered lamp posts
    output_layer = QgsVectorLayer("Point?crs=EPSG:28992", 'Filtered Lamp Posts', 'memory')
    output_layer_data = output_layer.dataProvider()
    output_layer_data.addAttributes(lamp_posts_layer.fields())
    output_layer.updateFields()

    # Processing each lamp post
    for lamp_post in lamp_posts_layer.getFeatures():
        lamp_post_geom = lamp_post.geometry()
        buffer_geom = lamp_post_geom.buffer(10, 5)  # Create a buffer of 10 meters

        buffer_area = buffer_geom.area()

        # Checking intersections with buildings
        intersection_area = 0
        for building in fixed_buildings.getFeatures():
            building_geom = building.geometry()
            if buffer_geom.intersects(building_geom):
                intersection_geom = buffer_geom.intersection(building_geom)
                intersection_area += intersection_geom.area()

                # Early exit: if more than 50% area is covered, skip this lamp post
                if intersection_area > buffer_area / 2:
                    break

        # Calculating free buffer area percentage
        free_area_percentage = (buffer_area - intersection_area) / buffer_area * 100

        # Add lamp post to output layer if free area is      60%
        if free_area_percentage >=60:
            output_layer_data.addFeature(lamp_post)
```

```
QgsProject.instance().addMapLayer(output_layer)

print(f"Filtered Lamp Posts layer created with {output_layer.featureCount()} features")
```

Appendix F

Check availability of free space around antennas

This chapter presents an example of how the availability of free space is assessed following the methodology shown in 24.
Add a buffer of radius 10 metres: For all the tall lamp posts a circle (QGIS terminology: buffer) around each tall lamp post was added by using the 'buffer' tool in QGIS.

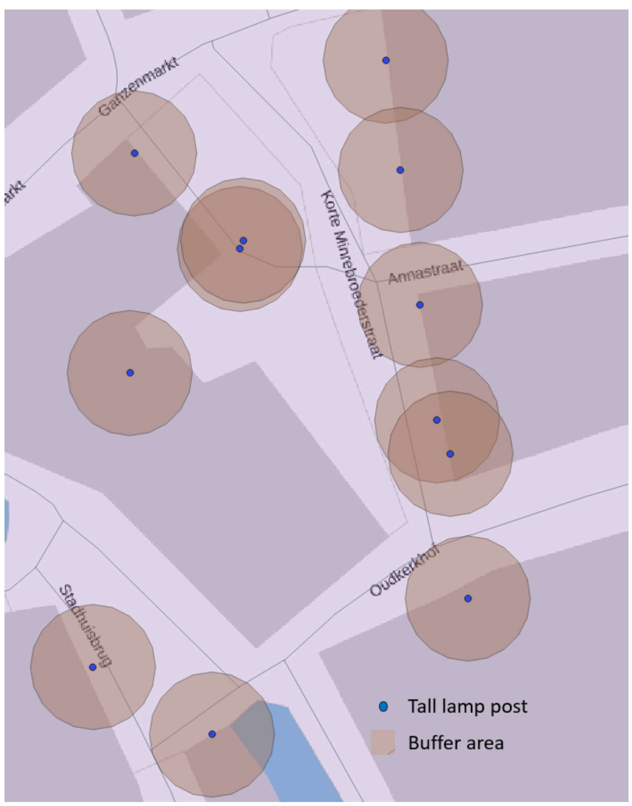

Figure 41: Buffer area for each tall lamp post

Clip buffer with intersecting buildings: A building layer was added from the open data sets available in PDOK, which added the building geometries in QGIS. By using the 'Clip' tool, the buffer area is clipped displaying the highlighted buffer area overlapping with the buildings.

Figure 42: Buffer area overlapping with buildings

Highlighting the buffer area free from buildings: By using the 'difference' tool, the area not overlapping with buildings (free space) is highlighted.

Figure 43: Example of buffer area not overlapping with buildings

Shortlist lamp posts: By highlighting the free spaces in the last step, it can be observed after visual inspection which lamp post has more free space without referring to the attribute table.

Figure 44: Example of visually comparable free space

In figure 44, it is clearly visible that out of the two lamps posts which one has the most available free space. So there is no need to refer to the attribute table (or follow the next step) to determine the choice for RU placement. Compare the buffer area free of buildings for each shortlisted lamp post: If it is not possible to understand which lamp post has more free space around it upon visual inspection, the attribute table is referred to compare the availability of free space. Then the lamp post with more free space is preferred.

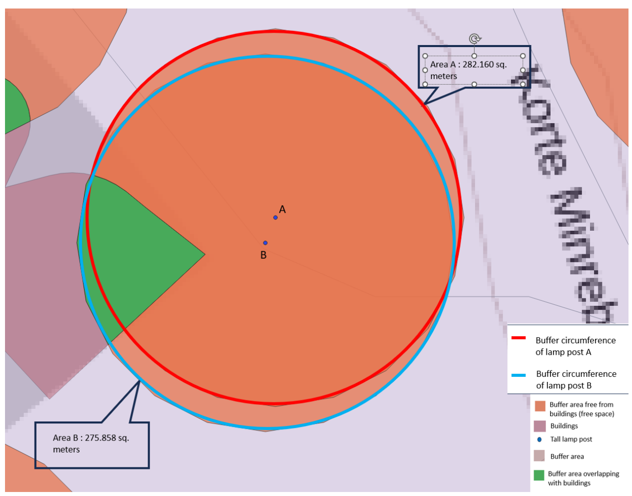

Figure 45: Example of comparison for free space between two adjacent lamp posts

In figure 45, it can be observed that lamp post A has 282.160 sq. metres of free space and lamp post B has 275.858 sq. metres of free space. Therefore lamp post A, with more free space available than B will be preferred for the placement of RU.

Appendix G

Cost calculation tables

This chapter presents the cost analysis for the proposed RU locations at Neude, Catherijnesingel and Korte Minrebroederstraat for the wharf cellar and base station QGIS scenarios.

Table 16: Cost estimation for placing a RU at Neude connected to the DU at the Stadhuisbrug wharf cellar

RU location: tall lamp post	**DU and CU location: wharf cellar**	**Distance (m)**	
136585, 456176	**136619.97, 455989.18**	**254.481**	
Neude	**Stadhuisbrug**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	254.481	25448.1
Power/meter	0.1	254.481	25.4481
fiber/m	50	254.481	12724.05
Installation Cost			1000
Backhaul			32000
Total			**≈83700**

Table 17: Cost estimation for placing a RU at Vredenburgplein connected to the DU at the Stadhuisbrug wharf cellar

RU location: tall lamp post	**DU and CU location: wharf cellar**	**Distance (m)**	
136335.9, 456023.3	**136619.97, 455989.18**	**356.573**	
Vredenburgplein	**wharf cellar**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	356.573	35657.3
Power/meter	0.1	356.573	35.6573
fiber/m	50	356.573	17828.65
Installation Cost			1000
Backhaul			32000
Total			**≈99030**

Table 18: Cost estimation for placing a RU at Korte Minrebroederstraat connected to the DU at the Stadhuisbrug wharf cellar

RU location: security camera pole	**DU and CU location: wharf cellar**	**Distance (m)**	
136678, 456016	**136619.97, 455989.18**	**110.32**	
Korte Minrebroederstraat	**Stadhuisbrug**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	110.32	11032
Power/meter	0.1	110.32	11.032
fiber/m	50	110.32	5516
Installation Cost			1000
Backhaul			32000
Total			**≈62060**

Table 19: Cost estimation for placing a RU at Neude connected to the DU at the Neude KPN base station

RU location: tall lamp post	**DU and CU location: KPN base station**	**Distance (m)**	
136585, 456176	**136528, 456107**	**140.5043295**	
Neude	**Neude**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	140.5043295	14050.43295
Power/meter	0.1	140.5043295	14.05043295
fiber/m	50	140.5043295	7025.216475
Installation Cost			1000
Backhaul			32000
Total			**≈66590**

Table 20: Cost estimation for placing a RU at Vredenburgplein connected to the DU at the Neude KPN base station

RU location: **tall lamp post**	**DU and CU location** **KPN base station**	**Distance (m)**	
136335.9, 456023.3	**136528, 456107**	**345.87**	
Vredenburgplein	**Neude**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	345.87	34587
Power/meter	0.1	345.87	34.587
fiber/m	50	345.87	17293.5
Installation Cost			1000
Backhaul			32000
Total			**≈97420**

Table 21: Cost estimation for placing a RU at Korte Minrebroederstraat connected to the DU at the Neude KPN base station

RU location: **security camera pole**	**DU and CU location:** **KPN base station**	**Distance (m)**	
136678, 456016	**136528, 456107**	**226.73**	
Korte Minrebroederstraat	**Neude**		
	Cost of 1 unit (€)	Number of units required	Total Cost (€)
RU	5000	1	5000
DU	2500	1	2500
CU	5000	1	5000
Digging/m	100	226.73	22673.42727
Power/meter	0.1	226.73	22.67342727
fiber/m	50	226.73	11336.71363
Installation Cost			1000
Backhaul			32000
Total			**≈79530**

Appendix H

Repository of images from QGIS, Google Street View Map and site visit

This chapter includes images sourced from QGIS, Google Maps, and site visits, which were directly or indirectly utilized in obtaining the results of this thesis. These visual references support the analysis and provide context for the findings presented.

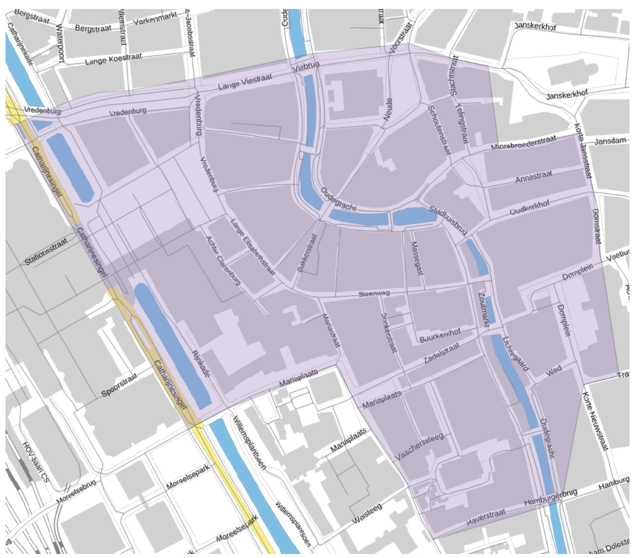

Figure 46: Research area of 307125.262sq. kilometres

Figure 47: Security camera poles

Figure 48: Bridges across the canals made of stones

Figure 49: Stedin managed wharf cellar

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