WIK-Consult • Report

Study for Stokab

Neutral fibre as a platform for innovation

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Contents

List of figures and tables

1 Executive summary

1.1 Stockholm as an innovation leader

The Digital Decade Policy Programme of 2022[1] establishes a number of high level digital targets which should be met across the EU by 2030. These include ensuring that all end-users are served by a **gigabit network** up to the network termination point, delivering at least **10,000 climate neutral high secure edge nodes** offering access to data services with low latency (i.e. a few milliseconds) wherever businesses are located and ensuring that the EU has its first computer with quantum acceleration by 2025, paving the way to be at the **cutting edge of quantum capabilities** by 2030. The Digital Decade Programme also seeks to support the growth of innovative scale-ups and **double the number of unicorns.**

By establishing a neutral dark fibre network, and actively supporting innovation hubs and the development of smart city solutions, the City of Stockholm has provided a foundation for Stockholm to meet the Digital Decade targets and to cement its position as the leading region in Europe for innovation.

According to the latest regional EU Innovation Scoreboard,[2] Stockholm holds the highest innovation rank "innovation leader +", ranking fourth overall in all EU regions. Stockholm is home to Europe's most valuable private start-up Klarna, as well as providing the launchpad for other well-known companies such as Spotify, Mojang, and Skype. Stockholm scores particularly highly on the number of scientific publications, the number of patents and the number of SMEs introducing product innovations, innovative business processes, sales of new-to-market and new-to-firm innovations.

In this study, with the aid of interviews and case studies, we explore how Stokab's dark fibre network has enabled the development of leading edge communication technologies as well as supporting the provision of high-tech applications in the field of audio-visual media, quantum computing and smart cities.

1.2 The City of Stockholm's neutral fibre network

Stokab was set up in 1994 by the City of Stockholm to build a competition-neutral IT-infrastructure capable of meeting future communication needs, spur economic activity, competition, diversity and freedom of choice. Stokab's network involves around 1.9 bln km of fibre, packed into 9,900 km of fibre optical cables. Nearly all educational and research facilities in the Stockholm area are served by the fibre network, as well as Stockholm's centre of innovation Kista.

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1 https://eur-lex.europa.eu/eli/dec/2022/2481/oj
2 See: Regional innovation scoreboard, https://research-and-innovation.ec.europa.eu/statistics/performance-indicators/regional-innovation-scoreboard_en; Innovation Index; accessed November 28th 2023

Stokab focuses on deploying passive infrastructure (dark fibre) and operates its business on a wholesale only basis. Its aim is to focus on providing the essential infrastructure, dark fibre, on which customers can add active equipment and develop services and applications to meet a wide variety of different needs.

1.3 Supporting innovation in connectivity

The availability of dark fibre to ISPs, research institutes and companies has contributed to Stockholm becoming a testbed for the latest communication technologies.

The Stokab dark fibre network enabled the competitive deployment of 4G networks, and is now supporting the deployment of ultrafast 5G networks in Stockholm. Based on data from Speedtest, as of Q2 2022[3] Stockholm was found to have the fastest 5G download speeds in a benchmark of Nordic cities. Alternative mobile network operators were offering faster speeds than the incumbent.

Specialist ISPs such as Layer & Mesh have been able to use advanced protocols such as TRILL over dark fibre to meet the needs of the most advanced businesses. Layer & Mesh offer latencies of less than 0.1 milliseconds to nearby data centres, and can provide **100/100 Gbit/s** within 10 days to 93% of all buildings in Stockholm.

Moreover, **with the aid of dark fibre from Stokab, the Royal Institute of Technology (KTH) and Ericsson established the first quantum communication link in the EU** and are collaborating to develop quantum secure networks, which will be essential when existing encryption methods are rendered obsolete as a result of quantum computing power. This is a first crucial step in a journey that could lead to the development of a quantum Internet which can support distributed quantum computing, quantum teleportation, and quantum key distribution as well as other-yet-to-be-discovered applications.

1.4 Supporting innovation over the top

Dark fibre has also enabled the provision of services such as “High Performance Computing” as a service and is supporting innovation in Stockholm’s creative industries, transport and environmental management.

Just one high definition video signal requires 1.5 Gbit/s, while ultra-high-definition requires 12 Gbit/s if uncompressed, but as “Mobile Links”, a company providing connectivity for events in the field such as the Stockholm marathon observes, 16 wavelengths over a single fibre can achieve 1.6 Tbit/s easily, and above if needed, which should meet all reasonable needs for the foreseeable future.

Fibre in the street has also supported experimentation in Smart City solutions. On Hornsgatan Street, the Swedish research institute RI.SE has been collaborating with

3 https://www.ookla.com/articles/nordics-sweden-denmark-5g-performance-q3-2022

other players such as Edeva to create an innovation and climate testbed zone in which various sensors, including radar and cameras, are used to capture information about traffic patterns and driver behaviour. Using licence-plate recognition, it is possible to assess whether the vehicles are complying with traffic regulations such as avoiding bus lanes and meeting environmental standards on vehicle emissions. Cameras in particular have significant bandwidth needs. If uncompressed, 1 hour of 4K video could consume 1.3 terabytes and require 6 Gbit/s for effective transmission.

1.5 Conclusions

The City of Stockholm's strategy in boosting innovation provides a number of insights that could help other administrations across the EU in contributing to the achievement of the Digital Decade targets and Europe's wider innovation goals.

- The example of Stockholm shows that a truly futureproof network that allows fibre unbundling, i.e. a **point to point fibre network, can enable innovation** in communications technologies as well as supporting applications in a diverse range of fields.
- High Performance Computing, which is critical for the evolution of big data processing[4] as well as **Quantum communications**, which will be essential for the security of networks in a quantum computing environment, **can only be supported over point to point fibre connections**
- Although it is not the only possible solution, **public ownership of dark fibre networks can help to ensure that research facilities and centres of public interest including schools and hospitals are effectively served** with open and future-proof infrastructure. A variety of communication services and applications can then be provided over the top in the open market.
- The wide and growing range of applications for dark fibre – from the creative industries to smart cities to connections for homes and businesses, show that fibre is no longer just a communication infrastructure but an **essential platform for society and the economy.**

4 https://www.sciencedirect.com/science/article/abs/pii/S0167739X18317679

2 Introduction

In December 2022, the European institutions adopted a Decision establishing the Digital Decade Policy Programme.[5] The Decision establishes a number of high level digital targets which should be met across the EU by 2030. These include a goal to support secure, resilient, performant and sustainable digital infrastructures, where:

- all end-users are served by a **gigabit network** up to the network termination point, and all populated areas are covered by wireless networks with performance at least equivalent to 5G
- At least **10,000 climate neutral high secure edge nodes** are deployed to guarantee access to data services with low latency (i.e. a few milliseconds) wherever businesses are located; and
- By 2025, the Union has its first computer with quantum acceleration, paving the way for the Union to be at the **cutting edge of quantum capabilities** by 2030

In addition, the Policy Programme envisages that at least 75% of enterprises should have taken up cloud computing, big data and/or AI, more than 90% of SMEs should reach at least a basic level of digital intensity, public services should be accessible online, and citizens and business should be able to interact online with public administrations.

By establishing a neutral dark fibre network, and actively supporting innovation hubs and the development of smart city solutions, the City of Stockholm has provided a foundation for Stockholm to meet the Digital Decade targets and to cement its position as the leading region in Europe for innovation.

In this study, with the aid of interviews and case studies, we explore how Stokab's dark fibre network is enabling cutting edge communication technologies and high-tech applications in the field of audio-visual media, quantum computing and smart cities.

- Chapter 3 highlights the factors that have made Stockholm a leader in innovation in Europe
- Chapter 4 describes Stokab's origins, business model and the technological architecture of its network
- In Chapter 5, we explore the advanced communication capabilities that have been enabled by Stokab's dark fibre infrastructure including some of the first trials in Europe in quantum communications
- Chapter 6 describes how the network has supported innovation in applications ranging from smart cities through to audiovisual media and quantum computing
- In Chapter 7, we discuss what lessons can be learned from Stockholm to help Europe achieve its innovation goals

5 https://eur-lex.europa.eu/eli/dec/2022/2481/oj

3 Stockholm as an innovation leader

In this chapter, we explore how Sweden has performed in innovation rankings and the role that Stockholm has played in fostering start-ups. Key findings are that:

- According to the latest regional EU Innovation Scoreboard, Stockholm holds the leading position for innovation amongst all regions in the EU and surrounding area.
- Stockholm is home to Europe’s most valuable private start-up Klarna, as well as providing the launchpad for other well-known companies such as Spotify, Mojang, and Skype
- When compared with other leading regions such as London, the Paris Region and Berlin, Stockholm scores particularly highly on the number of scientific publications, the number of patents and the number of SMEs introducing product innovations, innovative business processes, sales of new-to-market and new-to-firm innovations
- Public support has played an important role in fostering Sweden and Stockholm’s innovative culture. Sweden invests 0.8% of public funds in R&D, one of the highest rates worldwide. Stockholm is a leader in public private co-publications.

Sweden has long been identified as a leader in innovation within Europe. The 2023 European Innovation Scoreboard, found that Sweden ranks second behind Denmark amongst EU countries with an innovation performance of more than one third above the EU average.[6] Similar results have been found in the WIPO 2022 Global Innovation Index[7] which placed Sweden third out of 132 countries worldwide (and top in the EU), after Switzerland and the US.

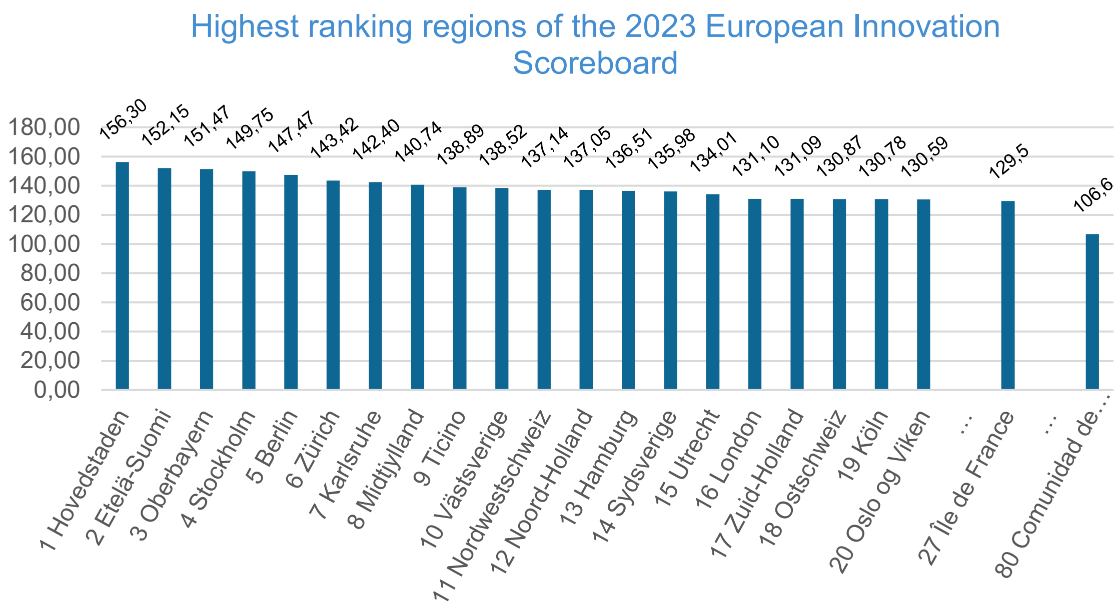
As the following Figure 3-1 shows, Stockholm has been a key driver of Sweden’s success. In fact, according to the EU Innovation Scoreboard, Stockholm holds a leading position for innovation amongst all regions in the EU and surrounding area. With a score of 147.47, the region ranks well above the EU average indexed at 100.00[8].

6 European Commission, 2023, European Innovation Scoreboard 2023; https://op.europa.eu/en/web/eu-law-and-publications/publication-detail/-/publication/04797497-25de-11ee-a2d3-01aa75ed71a1; p.5, accessed on October 28th 2023

7 WIPO 2022, Global Innovation Index 2022; https://8866495.fs1.hubspotusercontent-na1.net/hubfs/8866495/Global%20Innovation%20Index%202022.pdf, accessed on May 2nd 2023

8 See: European Union, Regional Innovation Scoreboard 2023, https://research-and-innovation.ec.europa.eu/statistics/performance-indicators/regional-innovation-scoreboard_en; accessed November 28th

Figure 3-1 Highest ranking regions of the 2023 European Innovation Scoreboard

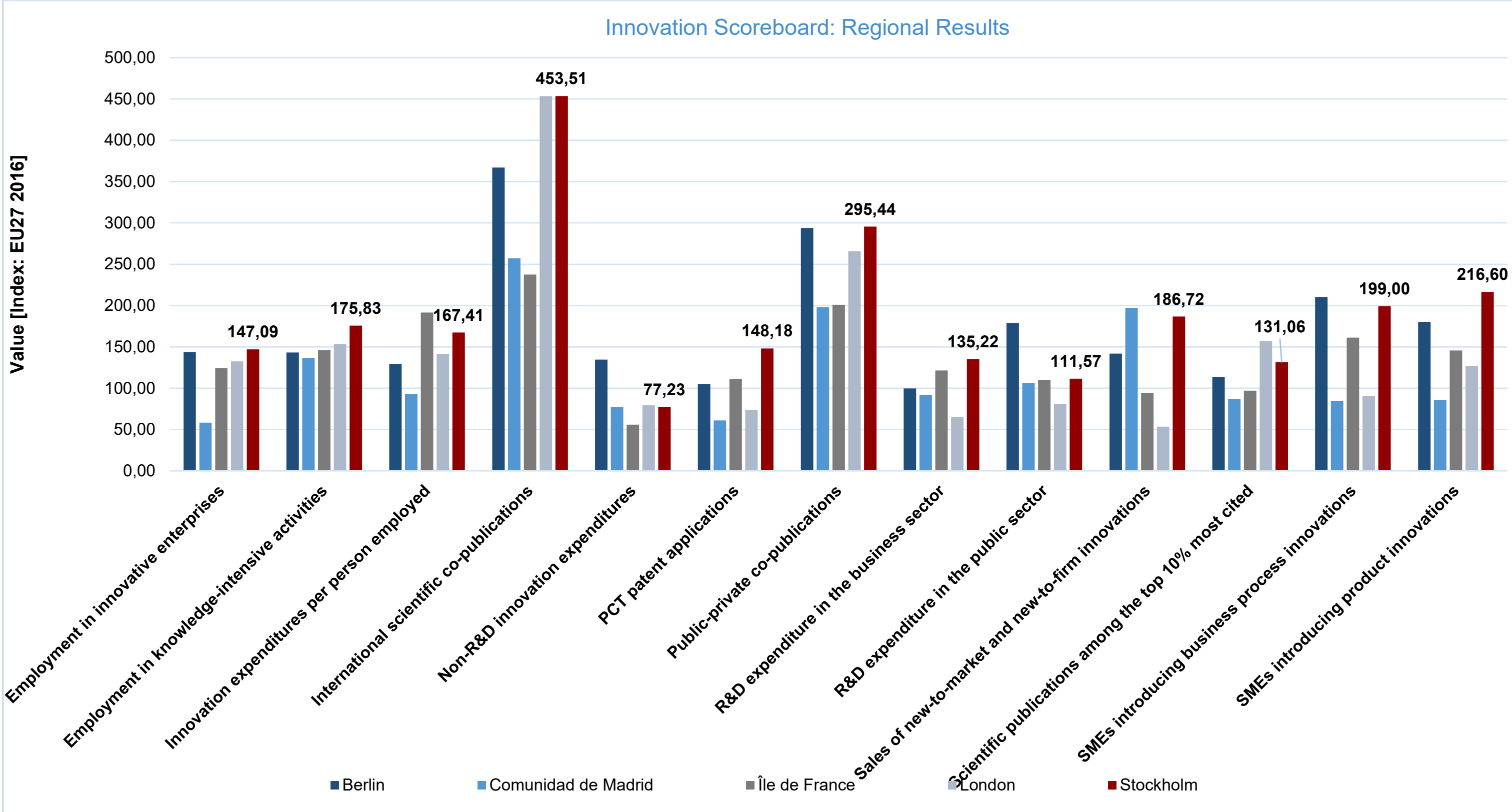


Source: European Innovation Scoreboard (EIS) / Regional innovation scoreboard 2023[9]

When compared with other leading regions such as London, the Paris Region and Berlin, Stockholm scores particularly highly on the number of scientific publications, R&D expenditure in the private sector, the number of patents and the number of SMEs introducing product innovations, innovation expenditures per person employed and sales of new-to-market and new-to-firm innovations.

9 See: European Union, Regional Innovation Scoreboard 2023, https://research-and-innovation.ec.europa.eu/statistics/performance-indicators/regional-innovation-scoreboard_en; accessed November 28th

Figure 3-2 Innovation Scoreboard 2023: Regional Results



Source: Source: European Innovation Scoreboard (EIS) / Regional innovation scoreboard 2023[10]

10 See: European Union, Regional Innovation Scoreboard 2023, https://research-and-innovation.ec.europa.eu/statistics/performance-indicators/regional-innovation-scoreboard_en; accessed November 28th

Looking further afield, Stockholm-based manufacturers of ICT and multimedia equipment also ranked fifth globally for patent applicants according to European Patent Office in 2022 with 1,827 patent applications[11].

Stockholm's high-tech infrastructure, research centres and skilled workforce have also encouraged significant inflows of venture capital and supported a vibrant start-up culture. As noted in a Dealroom 2021 tech ecosystem report,[12] Swedish start-ups raised a record €7.8bln in 2021 and Stockholm is home to Europe's most valuable private start-up Klarna, a financial services company. Other high profile start-ups based in Stockholm include:

- Spotify, music streaming
- Skype, VoIP communication software
- King, mobile game developer
- Mojang, makers of the popular game "Minecraft".[13]

Support from the public sector has also played a valuable role in stimulating Sweden's innovation culture. Sweden invests more than 3% of its GDP in Research & Development[14] of which 0.8% comes from public funding, one of the highest rates worldwide[15]. Several government agencies offer financial support or act as LPs to seed investors, making it possible for entrepreneurs in early stage to access funds. The government has also been active with pushing early access to new technology, including the "Home PC reform" of the late 1990s, through which 1 million Swedes were provided with their first computer and internet access.[16] As noted in the 2021 EU Innovation Scoreboard, Stockholm is also a leader in public private co-publications.

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11 EPO, 2023, https://www.epo.org/about-us/annual-reports-statistics/statistics/2022/statistics/applicants.html#tab2; accessed on 06.04.2023

12 Sweden Tech Ecosystem: Report 2021;https://si.se/app/uploads/2022/02/dealroom-sweden-tech-report-feb-2022.pdf, accessed May 2nd 2023

13 Felten, 2015, Stokab helps build a smarter Stockholm

14 Worldbank databank; https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS?locations=SE, accessed May 2nd 2023

15 Sweden, 2022, Investment in research pays off. Swedish innovation is ranked in the world top; https://sweden.se/work-business/study-research/research-in-sweden, accessed May 2nd 2023

16 Dealroom et al., 2022, Sweden Tech Ecosystem: Report 2021; https://si.se/app/uploads/2022/02/dealroom-sweden-tech-report-feb-2022.pdf, accessed May 2nd 2023

4 Stokab's neutral fibre network

Stockholm's innovation has been supported by a publicly owned, but independently financed[17] dark fibre network, Stokab. In this chapter, we look at the history behind Stokab, its network architecture and business model, and how a vision to deploy dark fibre more than 25 years ago, continues to provide the capabilities needed to support innovation today and in the years to come.

- Stokab was set up in 1994 by the City of Stockholm to build a competition-neutral IT-infrastructure capable of meeting future communication needs, spur economic activity, competition, diversity and freedom of choice. The Stokab network open to all on equal terms, was designed to meet the needs of operators and service providers, public administrations and wholly public owned enterprises as well the needs of public schools, childcare, leisure and culture.
- Stokab's network involves around 1.9 bln km of fibre, packed into 9,900 km of fibre optical cables. Nearly all educational and research facilities in the Stockholm area are served by the fibre network, as well as Stockholm's centre of innovation Kista.
- Stokab focuses on deploying passive infrastructure (dark fibre) and operates its business on a wholesale only basis. Its aim is to focus on providing the essential infrastructure, dark fibre, on which customers can add active equipment and develop services and applications to meet a wide variety of different needs.
- Each premise (multi-dwelling units and commercial buildings), is served with two point to point dark fibre access lines per household/company Access seekers can access these lines at around 400 access nodes around the city to collocate and install active equipment
- More than 100 Internet Service Providers (ISPs) make use of Stokab's infrastructure to offer ultrafast broadband to their customers. In addition to mass-market ISPs, this includes specialist business communication providers and mobile operators. In addition, Stokab supplies around 800 individual companies and organisations with dark fibre, enabling them to build their own network architecture depending on their needs.
- Fibres put into the ground by Stokab 25 years ago are still viable for today's use and for the foreseeable future. Stokab has also made provision for future expansion, by providing 8 spare fibres per building and deploying ducts which can accommodate additional fibres if needed. When digging the streets, Stokab deploys 2 ducts in parallel, each of which can accommodate 4 cables each with the size between 90 to 1,700 fibres.

17 Stokab does not rely on public funds, but is fully financed from earnings and loans

4.1 Stokab's history and objectives

Stokab, was set up in 1994 by the City of Stockholm to provide a passive fibre network to serve the highly knowledge-intensive Stockholm region. The aim of the company was to build a competition-neutral IT-infrastructure capable of meeting future communication needs, spur economic activity, competition, diversity and freedom of choice. The Stokab network, open to all on equal terms, was designed to meet the needs of operators and service providers, public administrations and wholly public owned enterprises as well the needs of public schools, childcare, leisure and culture.[18]

According to Stokab, its deployment strategy evolved in two phases. In the first phase, from 1994 until 2007, fibre was built on demand. The focus was to provide connectivity to public institutions such as universities and hospitals as well as major business sites and also to supply operators with fibre lines to connect the growing consumer market. In a second phase starting from 2007, the strategy shifted to meet growing demand from residential users and small businesses, and Stokab began deploying fibre pro-actively to households and offices in Stockholm (as well as to some premises in the surrounding area such as datacentres), with a goal of serving all multi-dwelling units and commercial premises.[19].

The City took the strategic decision to lease out dark fibre rather than spare ducts, since dark fibre can – in essence – be provided to an unlimited number of players, while duct space would be limited to only a few. The City also considered that a wholesale only model, in which fibre is treated as an essential infrastructure, similar to roads, would be best suited to support innovation and ensure equal treatment for all users of the network[20].

Stokab decided from the outset to build fibre using a future-proof point to point architecture that would meet future capacity needs and could enable competition and technological innovation through physical unbundling[21]. Environmental considerations were also paramount in the City's mandate. Besides fostering competition, diversity and freedom of choice, a key objective for Stokab has been to minimize digging in the city, decreasing congestion.[22] The City of Stockholm has also directed Stokab, via its

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18 Godlovitch et al., 2020, Neutral fibre and the European Green Deal, WIK Study for Stokab; https://stokab.se/download/18.15d457b6178eff38ee02ed/1619701526100/Neutral%20fibre%20and%20the%20European%20Green%20Deal%20,%20WIK-Consult.pdf, accessed on 23.03.2023

19 WIK online-interview with Stokab representatives Stefan Carlsson, CTO and Per-Olof Gustafsson, Senior Advisor and former Deputy CEO on March 23rd 2023

20 Further details about the wholesale only model, and how Stokab's structure compares with that of other firms are provided in the 2018 study by WIK-Consult The role of wholesale models in future networks and applications https://stokab.se/download/18.796da515175469f3e544f/1603888583380/The%20role%20of%20wholesale%20only%20models%20in%20future%20networks%20and%20applications%20(2018)%20WIK-Consult.pdf

21 Point-to-multipoint architectures do not allow for passive unbundling of fibres and thus limit the scope for product innovation by access seekers

22 Stokab; https://www.stokab.se/Om-oss/, accessed May 2nd 2023 extended fibre network to "provide the conditions to support the digitisation of the city and the business community, thereby enabling climate-smart solutions".[23]

4.2 Network coverage

Figure 4-1 shows the geographic footprint of Stokab's passive fibre network in the Stockholm area. Although it has a focus on Stockholm, Stokab also provides connections to Uppsala, Enköping, Eskilstuna, Södertälje, Nynäshamn as well as various islands of the Stockholm archipelago.

Figure 4-1 Stokab's fibre network geographic coverage

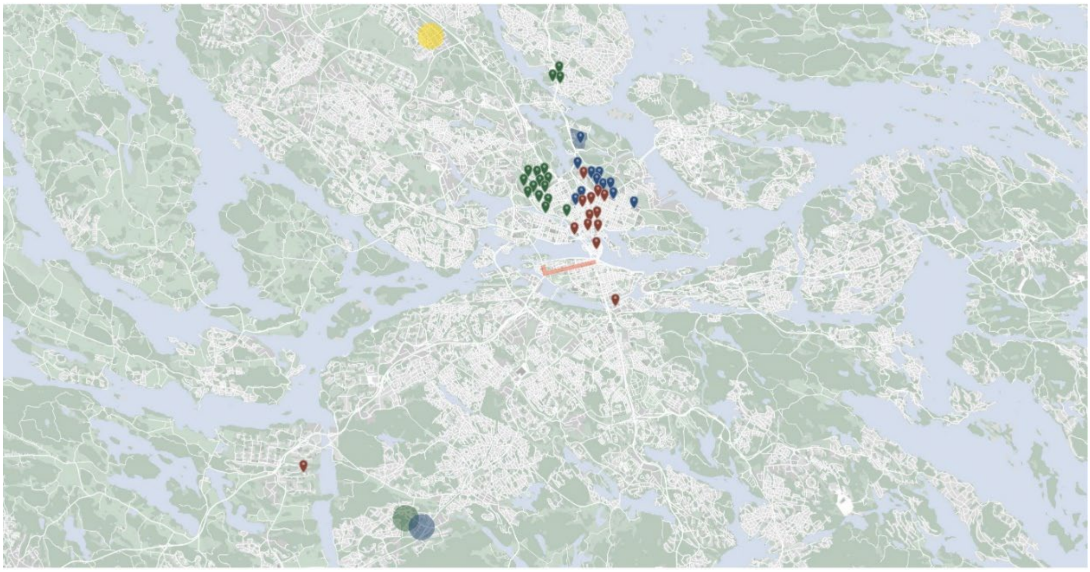
Source: Stokab; https://stokab.se/en/stokab/why-stokab/geographic-coverage, accessed on March 23rd 2023

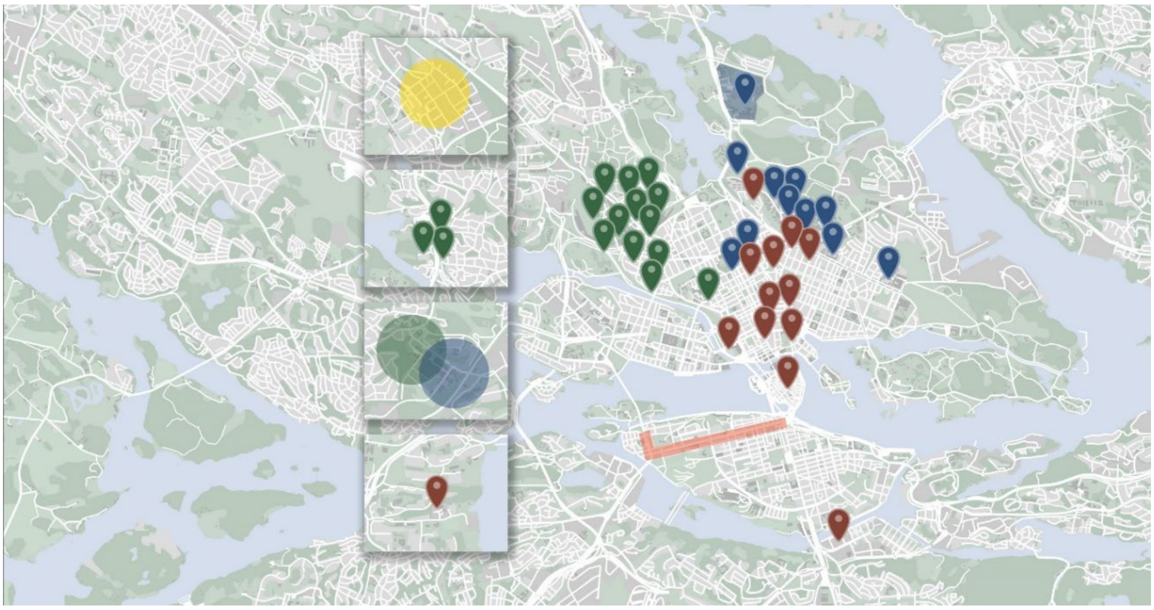
Stokab's network involves around 1.9 bln km of fibre, packed into 9,900 km of fibre optical cables. The network extends across 26 local authorities and reaches around 1 mln households (around 90% of the total)[24] and 99% of all business premises in the city of Stockholm [25].

As shown in Figure 4-2, Stokab's dense coverage and its focus on serving public interest locations means that **nearly all major healthcare, educational and research facilities in the Stockholm area are served by the fibre network**, as well as Stockholm's centre of innovation Kista.

23 Stokab; https://www.stokab.se/Om-oss/Foretagsfakta/, accessed May 2nd 2023
24 Stokab, 2020, The open access fibre network in Stockholm; http://conference2020.afor.ro/wp-content/uploads/sites/4/2020/03/Prezentare-STOKAB-Stockholm.pdf, accessed on March 23rd 2023
25 Stokab; https://stokab.se/en/stokab/why-stokab/flexible-network, accessed on March 23rd 2023

Figure 4-2 Stokab's coverage of universities and institutes, health and innovation centres





Note: Blue: Universities/institutes, Green: Medical Research institutes/university hospitals, Dark red: Start ups/Innovation hubs, Yellow: Kista Science City, Light red: Hornsgatan

Source: Stokab

4.3 Network architecture

Figure 4-3 shows how Stokab's network is structured. Each premise (multi-dwelling units and commercial buildings) is served with two point to point dark fibre access lines per household/company. Access seekers can access these lines at around 400 access nodes around the city to collocate and install active equipment[26]. At each access node, service providers can reach the property nodes in up to 40 buildings, which translates into up to

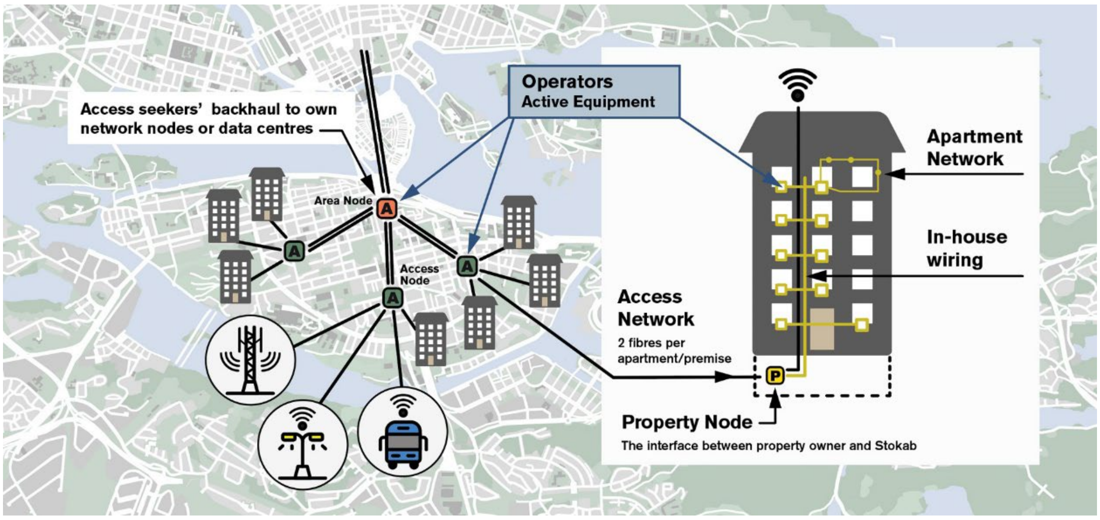
26 Stokab; https://stokab.se/en/stokab/why-stokab/network-and-security/the-nodes-and-cross-connect-switches; accessed on 30.03.2023

2000 apartments.[27] The access nodes are in turn aggregated into area nodes. From those nodes, access seekers can backhaul the traffic to their own network nodes or data centres. Around five different service providers are present at each node[28]. This network architecture enables more efficient deployment of active equipment, allowing savings in both cost and energy (and therefore lower environmental impact) than needing to install equipment in the case of each building, see figure 4-3. However, the network structure of course also enables the customer to install its active equipment in the basement.

The access nodes also enable the access seeker to connect mobile base stations and street furniture, such as bus stops, traffic light signals etc., for different smart city solutions.

In addition, Stokab operates around 600 cross connecting nodes, where the fibre routes of the dark fibre network intersect. At these locations Stokab can switch the fibre from one direction to another and thereby provide redundancy. This “cross connecting metro network” allows operators to take the most efficient route between the connected sites or redirect it in case of interruption.

Figure 4-3 Stokab’s network architecture



Source: Stokab

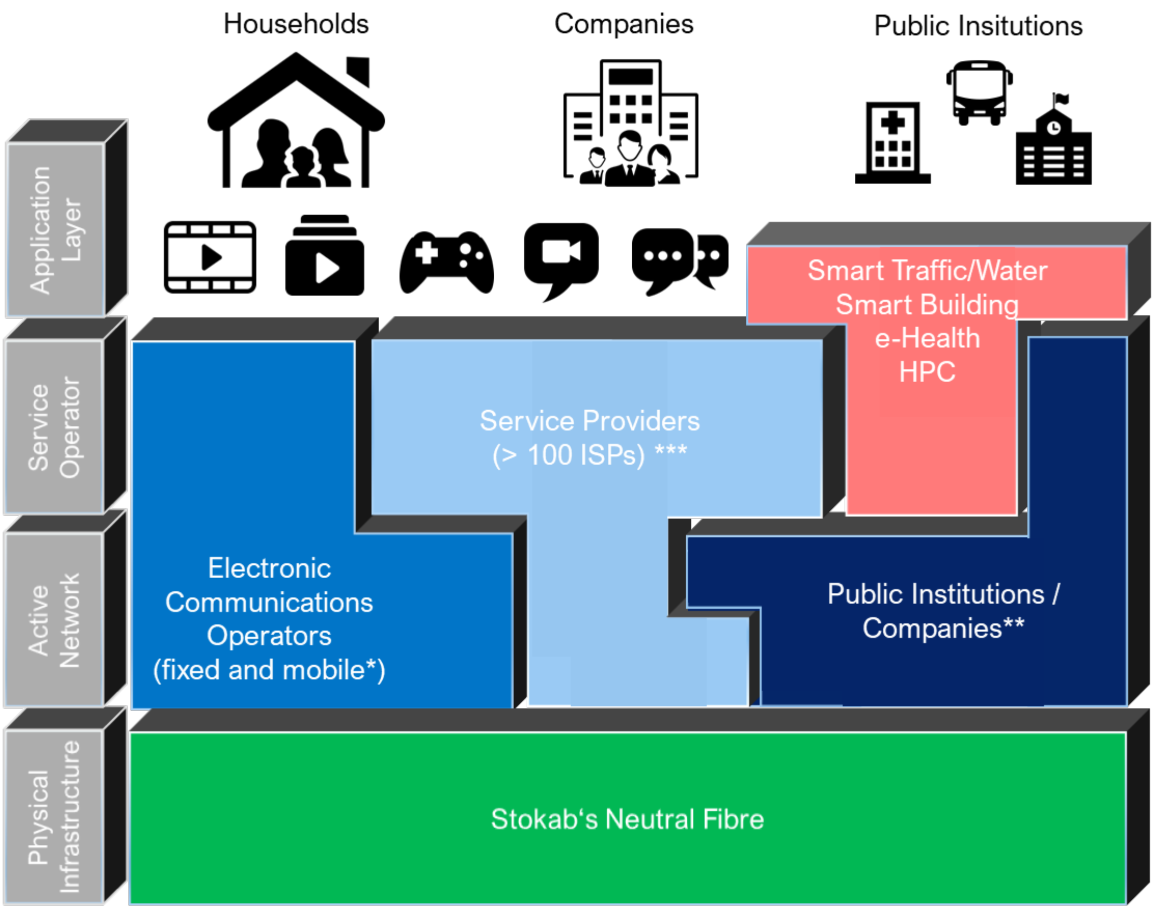
4.4 Stokab’s business model

Stokab focuses on deploying **passive infrastructure** (dark fibre) and operates its business on a **wholesale only** basis. Its aim is to focus on providing the essential infrastructure on which customers can add active equipment and develop services and applications to meet a wide variety of different needs.

27 Godlovitch et al., 2020, Neutral fibre and the European Green Deal and Stokab presentation, 2008
28 Godlovitch et al., 2020, Neutral fibre and the European Green Deal, WIK Study for Stokab; https://stokab.se/download/18.15d457b6178eff38ee02ed/1619701526100/Neutral%20fibre%20and%20the%20European%20Green%20Deal%20,%20WIK-Consult.pdf, accessed on 23.03.2023

Figure 4-4 illustrates how the network supports a variety of different network operators and service providers, enabling innovation in network operation, and diversity in content and services.

Figure 4-4 Stokab's dark fibre as an enabler for competition and service diversity



* Including Backhauling for base stations for mobile networks

** Including the City of Stockholm's internal network S:t Erik Kommunikation; Public institutions and companies have the opportunity to access Stokab's neutral fibre. They can choose to either activate the network through a service provider / electronic communications operator or to activate the network themselves. On that active platform, they can then procure different services. Companies can also use Stokab's neutral fibre to provide end customer services like the access of dark fibres in the streets of Stockholm to provide broadcasting services of the city marathon. (see e.g. chapter 6.2)

*** Companies and institutions may also use services providers to activate the network

Source: WIK-Consult

More than 100 Internet Service Providers (ISPs) make use of Stokab's infrastructure to offer ultrafast broadband to their customers. Besides traditional mass-market suppliers, Stokab's open wholesale model (together with that of other municipal networks in Sweden) is able to support ISPs which aggregate access from different municipal networks to offer an active wholesale service to ISPs, such as OpenNet and Zitius.[29] In a previous study, WIK-Consult found that the nature of retail services and consumer purchasing behaviour may also have been affected by the widespread choice in

29 Godlovitch et al., 2017, A tale of five cities: The implications of broadband business models on choice, price and quality, WIK Study for Stokab

broadband services supported by the wholesale only model. Specifically, Swedish consumers are more likely to buy broadband independently from other services such as fixed telephony and content than in countries characterised by vertically integrated telecom providers. This in turn may have supported greater use of a diverse range of content provided over-the-top (OTT).[30]

The neutral dark fibre business model also supports ISPs which focus on specific customer groups such as businesses. One example is Layer & Mesh, an ISP which focuses on business customers which have high demands on bandwidth and reliability (see case study in section 5.1).

Stokab also provides fibre for **mobile backhaul**. For example, Net4Mobility,[31] a joint venture between Tele2 and Telenor Sweden, is operating major parts of its mobile network in the Stockholm area on the basis of fibre backhaul from Stokab[32].

Stokab also provides **dark fibre directly to enterprises** such as banks, businesses, media and companies from the sectors of security, pharmaceutics, construction and manufacturing, as well as serving publicly owned entities like **public institutions** (schools, hospitals, traffic management) and housing companies. As of 2023 around 800 individual companies and organisations are making use of this possibility[33]. These directly connected customers can activate the fibres themselves or commission a service provider to support with the operation of the network.

The city itself is also making use of this possibility, through S:t Erik Kommunikationa subsidiary of Stokab. S:t Erik Kommunikation is responsible for the management and development of the city's internal communications network, and provisions services to around 2,250 addresses, some 42,000 City employees and 100,000 students in the city of Stockholm[34]. It operates only internally within the City of Stockholm. Through S:t Erik Kommunikation a neutral platform is created, on which the City and its organisations can purchase services in open competition on the market (e.g. data communication of all internal and external communication and telephony as well as data systems, applications and different technical solutions supporting the different administrations and companies within the City). Services for the City of Stockholm also includes kindergartens, schools and cultural facilities.

Stokab's passive network enables network operators and individual customers such as banks, hospitals and enterprises to build their own network architecture depending on their needs. As there is no hierarchy in the transport from one node to another, the end

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30 Idem
31 Net4Mobility; https://net4mobility.com/page/home/, accessed May 2nd 2023
32 Godlovitch et al., 2017, A tale of five cities: The implications of broadband business models on choice, price and quality, WIK Study for Stokab; https://stokab.se/download/18.52d820ca1732323a3ca4eb/1594711942698/A%20tale%20of%20five%20cities:%20The%20implications%20of%20broadband%20business%20models%20on%20choice,%20price%20and%20quality%20(2017),%20WIK-Consult..pdf, accessed on 23.03.2023
33 WIK online-interview with Stokab representatives Stefan Carlsson, CTO and Per-Olof Gustafsson, Senior Advisor and former Deputy CEO on March 23rd 2023
34 Stokab, https://stokab.se/det-har-ar-stokab/vilka-vi-ar/st-erik-kommunikation-ab; accessed on 23.03.2023

points of a communication link can all be provided through direct fibre links without any intermediate aggregation nodes, which could otherwise cause delays and other bottlenecks. In addition, cross connectors offer additional routes providing flexibility and redundancy.[35]

4.5 Conditions for access

Dark fibre from Stokab is offered at the same non-discriminatory conditions to every customer[36]. Discounts are offered based on volumes and the commitment time for the contract. [37] In addition, differentiated Service Levels are available to meet the differing needs of residential and business customers, including those with very demanding requirements.

Benchmarks, as well as feedback from interviews conducted in the context of this study, have shown that charges for dark fibre in Stockholm compare favourably with those in other major cities. For example, a 2015 study by United Minds, which compared charges for business connectivity based on fibre connections of 100 Mbit/s and 1 Gbit/s as well as of the average prices for dark fibre between five European cities showed that Stockholm had substantially lower prices than the other major cities considered. Dark fibre was also not readily available in all cases (see Figure 4-5).[38]

Figure 4-5 Broadband and dark fibre pricing across six European cities, 2015

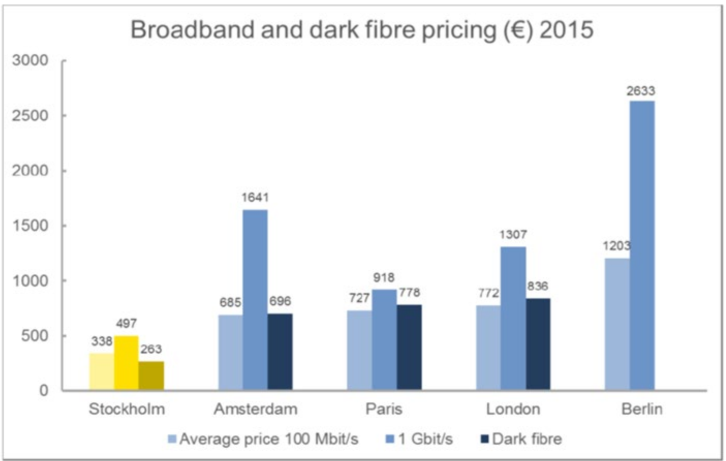

Figure 1: Average price per month (EUR) based on 36 monthly fees and connection fee – 100 Mbit/s, 1Gbit/s, and dark fibre.

Source: United Minds (2015).

In addition to Stokab's public service ethos, which focuses on the provision of essential infrastructure rather than profit maximisation[39], another factor that has contributed to low

35 WIK online-interview with Stokab representatives Stefan Carlsson, CTO and Per-Olof Gustafsson, Senior Advisor and former Deputy CEO on March 23rd 2023
36 Provins, 2017, Competition, innovation and growth,
37 Stokab, 2017, Stokab – The Foundation for IT in Stockholm
38 United Minds, 2015, The corporate price of high-speed broadband: A comparative Study between five European cities.
39 See Felten, 2015, Stokab helps build a smarter Stockholm

dark fibre prices in Stockholm is infrastructure competition from the incumbent Telia as well as the Com Hem[40] network that was merged with Tele2 in 2018[41].

4.6 A future proof network

Stokab's original decision to deploy point to point fibre in ducts is a key element that has ensured that the network is future-proof. Although Stokab deployed its first fibres in the 1990s, according to Per Olof Hedekvist, Senior Scientist at the Swedish public research institute RI.SE, improvements in fibre technology have not significantly impacted the potential capacity. This means that **fibres put into the ground by Stokab 25 years ago are still viable for today's use and for the foreseeable future**.

In addition, Stokab has made provision for both spare fibre and spare duct infrastructure for the deployment of additional connections.

For example, in addition to providing two point-to-point fibres for each apartment, **additional 8 spare fibres** are provided per building (residential and corporate) to meet future demand. Extra fibres are also reserved at each node to support future deployment to new buildings or roll-out of additional fibres (in addition to the existing spare fibre capacities).[42] Stokab relies on ribbon fibres, cables that hold 8 fibres, which reduces the space needed for single fibres as well as providing operational efficiencies, as multiple fibres can be spliced at once[43].

Stokab also ensures that there is extra capacity in its ducts to deploy additional fibre when needed. When digging the streets, Stokab deploys **2 ducts in parallel**, each of which can accommodate four cables each accommodating between 90 to 1,700 fibres.

Improvements in the fibre technology have led to a reduction in the size of cables over time. Stokab could therefore change the cables if additional fibres are needed. However, this has not yet been necessary, due to the spare capacity that was originally provided when deploying ducts.

When Stokab first deployed its network in the 1990s, it was difficult to assess the actual demand for the capacity offered over a fibre connection. Moreover, it was not possible at that time to foresee how demand would develop in the future. However, the availability of dark fibre and its potential to allow access seekers to construct architecture based on their own needs ultimately drove demand, and the network has been conceived to offer ample capacity to support increasing bandwidth needs for the future.

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40 Com Hem is the country's largest national HFC operator, which covers around. 78 % of Stockholm's population with gigabit capable HFC-accesses; see Godlovitch et al., 2017, A tale of five cities: The implications of broadband business models on choice, price and quality, WIK Study for Stokab

41 See Tele2 press release 2018; https://www.tele2.com/media/news/2018/tele2-and-com-hem-combining-to-create-leading-integrated-connectivity-provider/, accessed May 3rd 2023

42 WIK online-interview with Stokab representatives Stefan Carlsson, CTO and Per-Olof Gustafsson, Senior Advisor and former Deputy CEO on March 23rd 2023

43 See for example: https://www.fiberopticom.com/info/what-is-the-difference-between-ribbon-fiber-op-51391301.html; accessed on 05.04.2023

5 Supporting innovation in connectivity

Stokab's dark fibre network has enabled innovation and experimentation in the development of communications networks. In this chapter, we look at how the Stokab network has supported advanced communication services for businesses and public institutions including research facilities, as well as fostering the development of quantum communications, a key requirement for secure communications in the future.

- The Stokab dark fibre network has enabled the competitive deployment of 4G networks, and is now supporting the deployment of ultrafast 5G networks in Stockholm. Based on data from Speedtest, as of Q2 2022 Stockholm was found to have the fastest 5G download speeds in a benchmark of Nordic cities. Alternative mobile network operators were offering faster speeds than the incumbent.
- Specialist ISPs such as Layer & Mesh have been able to use advanced protocols such as TRILL over dark fibre to meet the needs of the most advanced businesses. Layer & Mesh offer latencies of less than 0.1 milliseconds to nearby data centres, and have had no downtime in 6 years. Connections of 100/100 Gbit/s can be provided within 10 days to 93% of all buildings in Stockholm.
- With the aid of dark fibre from Stokab, the Royal Institute of Technology (KTH) and Ericsson established the first quantum communication link in the EU and are collaborating to develop quantum secure networks, which will be essential when existing encryption methods are rendered obsolete as a result of quantum computing power. This is a first crucial step in a journey that could lead to the development of a quantum Internet which can support distributed quantum computing, quantum teleportation, and quantum key distribution as well as other-yet-to-be-discovered applications.

5.1 A platform for 5G deployment

One of the key benefits of the neutral fibre networks available in Stockholm and certain other Swedish municipalities has been the potential to accelerate the deployment of new generations of mobile technology and support competition in mobile networks.

In a 2017 study[44], WIK-Consult found that average mobile speeds in Stockholm were the highest out of five major cities[45] analysed. Moreover, the speeds offered by alternative mobile operators were close to that of the incumbent Telia, in contrast with cities where alternative mobile operators did not have a dark fibre wholesale network available or their own established FTTH network in place.

44 https://stokab.se/download/18.52d820ca1732323a3ca4eb/1594711942698/A%20tale%20of%20five%20cities:%20The%20implications%20of%20broadband%20business%20models%20on%20choice,%20price%20and%20quality%20(2017),%20WIK-Consult.pdf

45 Hamburg, London, Madrid, Paris and Stockholm

The Stokab network has also played a key role in facilitating the deployment of 5G by alternative operators. A report by Ookla[46] in Q2 2022 found that the 3 alternative mobile operators offered higher download speeds via 5G than Telia Sweden. Moreover, **Stockholm was found to have the fastest 5G download speeds in a benchmark of Nordic cities**, with a median download speed of 540 Mbit/s.[47] In this context, Ookla noted that "It is not surprising that Stockholm performs well as it is often a testing ground for innovation — hosting a number of tech startups and scale-ups (such as Skype and Spotify) and one in ten people working in the digital tech sector."[48]

To illustrate this point, Staffan Ingvarsson, CEO of Stockholm Business Region and Board member of Stockholm Science City, conducts a video interview over the 5G mobile network in Stockholm's subway system. "I am not sure it would be possible in many cities to have this conversation under the city," he observes. "It is necessary to have the best possible physical as well as cultural infrastructure to be attractive," he says**. It is a point of pride for the City that despite having a population of only 1m, the city is served by 4 mobile operators offering 5G services.**

The network capabilities of two of the operators, Tele2 and Telenor Sweden, are provided by the Joint Venture "Net4Mobility". In an interview conducted for this study, Tele2 notes that they have been working with Stokab for the deployment of their mobile network in the Stockholm area ever since Stokab was founded and have continued to do so through the joint venture.

Kent Norman, manager for transmission and data at Tele2 explains that through Net4Mobility they are now deploying 5G using mid-band spectrum, which involves densifying the network with more cell sites and fibre. According to Norman, 5G standalone services may be possible in 2024.

"We profit from being independent of the incumbent and at the same time fibre availability pushes competition and forces everybody to be in the race", Kent Norman, Manager for transmission and data at Tele2

Stockholm, like many large Swedish cities, is in a good position for this roll out due to the availability of fibre. However, Norman notes that the challenge with 5G will be to reach smaller cities with around 5,000-10,000 inhabitants[49]. In the past, these were connected through microwave links, but with 5G fibre will be needed for transport as well as redundancy. In general, Tele2 has found that in around 95% of the cases, they have been able to secure competitive fibre links in urban areas of Sweden. **However, in other**

46 https://www.ookla.com/articles/nordics-sweden-denmark-5g-performance-q3-2022#:~:text=The%20Swedish%20capital%20of%20Stockholm,band%20and%20mid%2Dband%20spectrum.

47 Although average speeds have declined as the network was rolled out further and take-up increased, Stockholm ranks 11th in Ookla's global mobile speed city ranking conducted in September 2022, with an average download speed of 126.40 mbps. This speed makes it the fourth highest ranking in Europe following Copenhagen (2nd global, 157.54 Mbps), Oslo (3rd global, 155.19 Mbps) and Sofia (6th global, 145.28 Mbps).

48 Ookla, 2022, 5G in Nordics: Sweden Leads on Speeds, Denmark on 5G Availability; https://www.ookla.com/articles/nordics-sweden-denmark-5g-performance-q3-2022; accessed on May 2nd 2023

49 See also Frąckiewicz 2023, The challenges of implementing 5G in rural areas; https://ts2.space/en/the-challenges-of-implementing-5g-in-rural-areas/, accessed on May 2nd 2023

countries where Tele2 operates mobile services, accessing dark fibre has been more difficult and more expensive, especially in countries which do not have alternative fibre network providers.

Tele2 prefers in general to rely on alternative fibre providers for its backhaul. “We profit from being independent of the incumbent and at the same time fibre availability pushes competition and forces everybody to be in the race,” he says. While microwave links were efficient for deploying 2G, 3G and 4G networks, when it comes to 5G, particularly in urban and suburban areas, fibre is the preferred method for access, he says. Moreover, the capacity and quality available from dark fibre is higher than is available via the leased lines that are often marketed by incumbent operators.

Norman considers that in general **it is a good idea for cities to build their own fibre as an infrastructure if it is needed to support competition**. Building their own fibre is a way for cities to save money, and there is also the potential for them to earn money from private sales if they choose to do so, he notes.

5.2 Innovation in business connectivity

Another benefit from having dark fibre access readily available is that it enables innovation in the development of connectivity for businesses. A prime example in this field is Layer & Mesh, a wholesale connectivity provider founded in 2006, which specialises in offering services to customers in the Stockholm area with the highest demand for data transmission and latency, such as postproduction, banks, IT companies or architects with a high need for GPU.

> “Our network is really self-healing, we don’t even have to think about redundancy and there is no need for human interaction. We have not have a single outage for the past 6 years” – Daniel Persson, founder and CEO of Layer & Mesh

Since the beginning, Layer & Mesh has been using Stokab’s dark fibre, alongside fibre from other players, to roll out a meshed layer 2 and layer 3 network throughout Stockholm. In doing so, they have focused on differentiating their service through innovation in network design and active equipment. Layer Mesh CEO Daniel Persson notes that there was a need to build more robust networks, and this entailed moving beyond legacy transport protocols such as multiprotocol label switching (MPLS) to alternatives such as TRILL.

Daniel Persson notes that by using other transport protocols along with Stokab’s infrastructure and as much passive equipment as possible, they have succeeded in furthering network development. “Now we have a self-healing network that is redundant and decentralized,” he says. “This is a much more robust and powerful network that requires less maintenance and achieves low latency. We have a large amount of distribution nodes and a variety of different data centres directly connected to our network. We also have the possibility to deploy and apply resources into our meshed fibre network such as super computers.”

Layer & Mesh's networks are characterised by a flat network hierarchy, directly connected fibre without any intermediate technologies or protocols, which support the lowest levels of latency and jitter. The network utilises passive Coarse wavelength division multiplexing (CWDM), with up to 16 channels or wavelengths, and Layer & Mesh have designed their own small-form factor CWDM and installed it in nearly all commercial buildings in Stockholm.

Persson notes that over the past 4-5 years, their lowest capacity bandwidth has been 10 Gbps symmetric, they offer latencies of less than 0.1 ms to nearby data centres, and have had no downtime in 6 years. They have a 10 day delivery time on 100/100 Gbit/s to 93% of all buildings in Stockholm. The localized nature of the network and use of passive equipment has also enabled significant energy savings, as they don't need a power supply to most of their equipment racks.

"I think it is worthwhile keeping data separate from the internet where possible, and a lot of data should be processed in private networks," says Persson. "The natural solution is local resources and local transport. This can be both more cost effective and energy efficient." Persson notes that with more local storage, companies who are headquartered in Stockholm, but store their data in Ireland and Frankfurt, could save an extreme amount of energy, emissions (CO2)[50] and costs.

> "We prefer to rent from Stokab because other network operators try to sell capacities, Stokab sells dark fibres." – Daniel Persson, founder and CEO of Layer & Mesh

Although Layer & Mesh does not rely exclusively on Stokab for its network capacity, they prefer to work with Stokab where this is possible. "Stokab brings growth and competition to Stockholm. Neutral fibre is the ideal platform for all who want to provide well rounded services," says Persson. "Unfortunately, where Stokab is not active, there are monopolies in place which hinder development and competition. There is no way to build layer 2 networks or even comparable services in these areas. Other ISPs and city networks want to sell capacity and not dark fibre," he says.

5.3 Pushing the performance boundaries of fibre

One of the reasons that the dark fibre network installed by Stokab in the 1990s has proved so future-proof, is that there has been a significant progression in the bandwidths that fibre can support due to continual innovations in the active equipment driving the line. This is in contrast to developments in fibre technology itself, which have been more incremental and focused on reducing the size of the fibre and increasing its physical flexibility.

50 See also Obermann, 2020, Nachhaltigkeitsvergleich der Zugangsnetz-Technologien FTTC und FTTH; https://www.brekoverband.de/site/assets/files/4853/gutachten_nachhaltigkeitsvergleich_ftth_fttc.pdf, accessed May 2nd 2023

As Per Olof Hedekvist, Senior Scientist at RI.SE notes, at the time when Stokab was founded, speeds over fibre had reached between 10-20Gbit/s. The focus was first on how quickly to switch a laser on and off. The second stage was to increase the number of lasers that could be accommodated in each fibre, by packing laser signals closer together and improving filters. Today, research on improving modulation has delivered more wavelengths per fibre, as well as supporting more data per wavelength. Bandwidths of up to 400 Gbit/s are now possible for each wavelength[51]. Hedekvist does not expect significant improvements in bandwidths beyond the current levels, but notes that further enhancements could be achieved by facilitating the transmission of data in both directions on the same fibre.[52]

Research on improving modulation has delivered more wavelengths per fibre, as well as supporting more data per wavelength. Bandwidths of up to 400Gbit/s are now possible for each wavelength.

Hedekvist observes that while deployment of fibre and the equipment to achieve speeds of this kind is very expensive, fibre cables can support very high bandwidths over long distances. Thus, it is important to maximise their utilisation to ensure efficiency.

RI.SE rents dark fibre from Stokab and others to connect their offices as well as to connect to the university network in Sweden. Hedekvist supports the passive only wholesale only model pursued by Stokab. **According to Hedekvist, fibre should be viewed as an infrastructure and telecoms as a services, and it is beneficial for competition when the infrastructure is separated from the service, and they don't own one another**. He sees significant benefits in being able to rent a fibre pair without transmission equipment. When there is no amplifier that defines the direction of the fibre, it is possible to use the fibres for different purposes, sending data back and forth in each. Conversely, when renting a wavelength, the direction and stability of the wavelength are defined, so it is necessary to adapt to these parameters.

Hedekvist notes that routable optical networks (RONs), where routing is carried out at the level of wavelengths, rather than downstream protocols such as ethernet or IP, should be the way forward, but have not yet been implemented to his knowledge by RI.SE.

5.4 Supporting quantum communications

Besides delivering higher performance, an increasingly important application for dark fibre is its capability to support quantum communication, a technology which provides a mechanism for secure communication. The KTH Royal Institute of Technology is currently collaborating with Ericsson in quantum communication trials. The trial makes use of a Stokab fibre link to connect the KTH lab to Ericsson's lab in Kista, around 17km away.

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51 See also Cisco White Paper, 2022, Growing the Network with 400 Gbps Coherent Pluggable Optics; https://www.cisco.com/c/dam/en/us/solutions/collateral/service-provider/routed-optical-networking/white-paper-sp-400g-coherent-optics.pdf, accessed May 2nd 2023

52 Typically today, there is one fibre per direction. Transmitting data in two directions within the same fibre which may improve precision in timing, because the transmission characteristics in both directions are identical

The distance allows transmission without intermediate amplification. Quantum communications involves communicating with individual photons - sending and detecting one particle of light at a time.

The project is being led by Val Zwiller, Professor in Quantum Photonics at KTH, who has worked in this field for more than 20 years and by Dr. Gemma Vall Llosera, principal quantum engineer at Ericsson, Sweden. Prof. Zwiller explains that with quantum communications, security is assured by the laws of physics, rather than through traditional encryption, which can be decrypted by the massive computational power provided by quantum computers.[53] Quantum secure networks will be essential to support secure communications in an environment with high security needs.

"Secure quantum communications are important to keep democracy alive" – Val Zwiller, Professor in Quantum Photonics at KTH

For Ericsson, one of the application areas is to build a quantum internet. Quantum internet consists of a communication network built on quantum links and nodes that is able to distribute quantum entanglement between nodes. The nodes consist of quantum repeaters/memories that, in turn, are able to store the quantum states. Such networks could enable distributed quantum computing, quantum teleportation, and quantum key distribution as well as other-yet-to-be-discovered applications. In the meantime, the transparent fibre link has provided a first opportunity for research, yielding a patent, three master thesis, one PhD thesis, and evidence that secret random numbers were shared between KTH and Ericsson.[54]

Quantum communications can only be provided over point-to-point fibre and Prof. Zwiller observes that Stokab's fibre network was an essential element in making the research possible. "We were the first in the EU to have a quantum link," he notes. "Innovation would not have happened without this link. In any area you need good will and good collaboration for innovation to happen. It should also be a good investment for Stokab," he observes, "as this innovation could be transformed into a market 5 to 10 years from now." In contrast, he notes that high rents for dark fibre in countries such as Canada mean that connectivity costs form a major part of the research budget, placing additional burdens on scientists who already face challenges in obtaining funding.

53 https://www.newscientist.com/article/2353376-quantum-computers-can-break-major-encryption-method-researchers-claim/#:~:text=A%20group%20of%20researchers%20has,powerful%20enough%20to%20threaten%20encryption.

54 Research based on the KTH Ericsson link includes a doctoral thesis on Semiconductor quantum optics at telecom wavelengths http://kth.diva-portal.org/smash/record.jsf?aq2=%5B%5B%5D%5D&c=19&af=%5B%5D&searchType=SIMPLE&sortOrder2=title_sort_asc&query=katharina+Zeuner&language=en&pid=diva2%3A1499539&aq=%5B%5B%5D%5D&sf=all&aqe=%5B%5D&sortOrder=author_sort_asc&onlyFullText=false&noOfRows=50&dswid=-5676 as well as Masters theses and a peer-reviewed paper Samuel Gyger, Katharina D. Zeuner, Thomas Lettner, Sandra Bensoussan, Martin Carlnäs, Liselott Ekemar, Lucas Schweickert, Carl Reuterskiöld Hedlund, Mattias Hammar, Tigge Nilsson, Jonas Almlöf, Stephan Steinhauer, Gemma Vall Llosera, and Val Zwiller , "Metropolitan single-photon distribution at 1550 nm for random number generation", Appl. Phys. Lett. 121, 194003 (2022) https://doi.org/10.1063/5.0112939)

For now, the KTH Ericsson test bed involves one link, the first within the EU[55]. However, Prof. Zwiller would like to expand the network to include more nodes, covering the area East of Stockholm and eventually reaching all parts of Sweden. One solution is to design a network in a star shape, so that quantum information can be sent to and processed in a central hub. Start-ups such as Q-bird[56] in the Netherlands are working to develop hardware for such hubs. However, as key data rates decline with distance, further nodes and repeaters are needed for connections longer than 40km.

The European Commission has plans to support the extension of quantum communication infrastructure to cover the whole of the EU. In January 2023, the European Commission announced the implementation phase of the European Quantum Communication Infrastructure Initiative (EuroQCI),[57] which will support national projects to design and build national quantum communication networks, test and adapt technologies and protocols to meet the needs of each country. The importance of quantum research in Europe has also been recognised in the 2022 award for the Nobel Prize in Physics[58] which was awarded to three scientists[59] (including two Europeans), who have been involved in experiments using entangled quantum states, where two particles behave like a single unit even when they are separated.

However, as Prof. Zwiller observes, the EU is playing catch-up. China has funded thousands of researchers for more than 10 years to obtain a leading position in quantum communications. This will give them an opportunity to have truly secure communications that cannot be intercepted. They have already developed a quantum link stretching from Beijing to Shanghai, using 20 links to cover a total of 1,000km, with repeaters every 40km[60]. They also launched a satellite programme 7 years ago. Prof. Zwiller equates China's foresight in this area to its dedication to investing in battery capabilities for electric vehicles. There are also developments in the US (Boston), Cambridge in the UK, and Switzerland. Elon Musk is also reportedly considering investing in this area. Prof Zwiller highlights the need to extend Europe's ambition and provide for more research funding to support quantum communications development in the EU. "Secure quantum communications are important to keep democracy alive," he says.

> "We were the first in the EU to have a quantum link. Innovation would not have happened without this link from Stokab. In any area you need good will and good collaboration for innovation to happen." – Val Zwiller, Professor in Quantum Photonics at KTH

55 Other links exist in Geneva, Cambrigde, US and most in China
56 Qbird,;https://q-bird.nl/, accessed May 2nd 2023
57 European Commission, The European Quantum Communication Infrastructure (EuroQCI) Initiative; https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci, accessed May 2nd 2023
58 Nobel Foundation, 2022, Press release, The Nobel Prize in Physics 2022; https://www.nobelprize.org/prizes/physics/2022/press-release/, accessed May 2nd 2023
59 Alain Aspect Institut d'Optique Graduate School – Université Paris- Saclay and École Polytechnique, Palaiseau, France, John F. Clauser J.F. Clauser & Assoc., Walnut Creek, CA, USA, Anton Zeilinger University of Vienna, Austria
60 See also 2017 https://usa.chinadaily.com.cn/china/2017-09/30/content_32669867.htm , accessed May 2nd 2023

6 Supporting innovation over the top

In this chapter, through case studies and interviews, we consider how dark fibre and the innovations in network technology that it supports can foster innovation in the development of content, public sector services, research and industrial applications.

- Stokab's network has enabled the broadcasting of events such as the Stockholm Marathon, and UEFA matches, as well as popular shows such as "Dancing with Stars". Just one high definition video signal requires 1.5 Gbit/s, while ultra-high-definition requires 12 Gbit/s if uncompressed. As observed by "Mobile Links", a company providing connectivity for events in the field, 16 wavelengths over a single fibre can achieve 1.6 Tbit/s easily, and above if needed, which should meet all reasonable needs for the foreseeable future
- The readily available fibre in the street has supported experimentation in Smart City solutions. On Hornsgatan Street, the Swedish research institute RI.SE has been collaborating with other players such as Edeva to create an innovation and climate testbed zone in which various sensors, including radar and cameras, are used to capture information about traffic patterns and driver behaviour. Using licence-plate recognition, it is possible to assess whether the vehicles are complying with traffic regulations such as avoiding bus lanes and meeting environmental standards on vehicle emissions. Cameras in particular have significant bandwidth needs. If uncompressed, 1 hour of 4K video could consume 1.3 terabytes and require 6 Gbit/s for effective transmission.
- The fastest supercomputers will be essential for the future development of various use cases including genetic analysis, environmental assessments, and support for economics and finance. The dense dark fibre networks available in Stockholm will ensure that the City is well-placed when it comes to deploying and using High Performance Computing facilities in real time.

6.1 Access to High Performance Computing power

The very high bandwidths, low latency and reliability offered by Stokab's dark fibre network have the potential to support a range of industrial applications. One such application is the ability to make use of High Performance Computing (HPC) to address scientific and engineering problems that are so demanding that computations cannot be performed using general-purpose computers. HPCs (also sometimes referred to as supercomputers) involve powerful systems with parallel computing units comprising tens or hundreds of thousands of processors. The fastest supercomputers today can operate hundreds of petaflops[61] of floating point operations per second.

As shown in the following table, HPCs are essential for the future development of various use cases in engineering, life sciences and social science. Examples include genetic analysis, environmental assessments, and support for economics and finance.

61 One petaflop is 10^15 (one thousand million million)

Table 6-1 Fields of HPC applications

Number	Discipline	Panels
1	Physical Science and Engineering	Mathematics: all areas of mathematics, pure and applied, plus mathematical foundations of computer science, mathematical physics and statistics
2		Fundamental constituents of matter: particle, nuclear, plasma, atomic, molecular, gas, and optical physics
3		Condensed matter physics: structure, electronic properties, fluids, nanosciences
4		Physical and analytical chemical sciences: analytical chemistry, chemical theory, physical chemistry/chemical physics
5		Synthetic chemistry and materials: materials synthesis, structure-properties relations, functional and advanced materials, molecular architecture, organic chemistry
6		Computer science and informatics: informatics and information systems, computer science, scientific computing, intelligent systems
7		Systems and communication engineering: electronic, communication, optical and systems engineering
8		Products and processes engineering: product design, process design and control, construction methods, civil engineering, energy systems, material engineering
9		Universe sciences: astro-physics/chemistry/biology; solar system; stellar, galactic and extragalactic astronomy, planetary systems, cosmology, space science, instrumentation
10		Earth system science: physical geography, geology, geophysics, atmospheric sciences, oceanography, climatology, ecology, global environmental change, biogeochemical cycles, natural resources management
11	Life Sciences	Molecular and Structural Biology and Biochemistry: molecular biology, biochemistry, biophysics, structural biology, biochemistry of signal transduction
12		Genetics, Genomics, Bioinformatics and Systems Biology: genetics, population genetics, molecular genetics, genomics, transcriptomics, proteomics, metabolomics, bioinformatics, computational biology, biostatistics, biological modelling and simulation, systems biology, genetic epidemiology
13		Cellular and Developmental Biology: cell biology, cell physiology, signal transduction, organogenesis, developmental genetics, pattern formation in plants and animals
14		Physiology, Pathophysiology and Endocrinology: organ physiology, pathophysiology, endocrinology, metabolism, ageing, regeneration, tumorigenesis, cardiovascular disease, metabolic syndrome
15		Neurosciences and neural disorders: neurobiology, neuroanatomy, neurophysiology, neurochemistry, neuropharmacology, neuroimaging, systems neuroscience, neurological disorders, psychiatry
16		Immunity and infection: immunobiology, aetiology of immune disorders, microbiology, virology, parasitology, global and other infectious diseases, population dynamics of infectious diseases, veterinary medicine
17		Diagnostic tools, therapies and public health: aetiology, diagnosis and treatment of disease, public health, epidemiology, pharmacology, clinical medicine, regenerative medicine, medical ethics
18		Evolutionary, population and environmental biology: evolution, ecology, animal behaviour, population biology, biodiversity, biogeography, marine biology, ecotoxicology, prokaryotic biology
19		Applied life sciences and biotechnology: agricultural, animal, fishery, forestry and food sciences; biotechnology, chemical biology, genetic engineering, synthetic biology, industrial biosciences; environmental biotechnology and remediation
20	Social Sciences and Humanities	Individuals, institutions and markets: economics, finance and management
21		Institutions, values, beliefs and behaviour: sociology, social anthropology, political science, law, communication, social studies of science and technology
22		Environment, space and population: environmental studies, demography, social geography, urban and regional studies
23		The Human Mind and its complexity: cognition, psychology, linguistics, philosophy and education
24		Cultures and cultural production: literature, visual and performing arts, music, cultural and comparative studies
25		The study of the human past: archaeology, history and memory

Source: PRACE / European Commission, Supporting the implementation of CEF2 Digital - SMART 2017/0018, p. 154[62].

However, accessing these resources requires high quality and resilient connectivity, which today can only be provided over point to point fibre networks, while backbone connections linking different HPC resource centres require fibre-based terabit connectivity.[63] Connectivity requirements will be particularly intense when the use of HPC resources moves from the current practice of "batch" processing to the real-time exchange of data and associated processing.

The availability of dark fibre from city networks such as Stokab has enabled Stockholm to take a leading role in the development and use of HPC facilities. The KTH Royal Institute for Technology in Stockholm hosts Sweden's PDC Center for High Performance Computing,[64] and Sweden was host to the EuroHPC Summit in 2023, an event which attracted nearly 600 participants to discuss exascale computing and its implications for European and industry as well as advances in quantum computing. The ready availability of high performance fibre connections enabling connectivity between data centres, businesses and SMEs has also enabled the provision of HPC as a service from Stockholm's innovation district.[65]

6.2 Broadcasting and media

Streaming video is one of the most bandwidth intensive activities for consumers[66]. However, significantly more bandwidth is required in the process of filming.

Mobile Links supports broadcasters by providing connectivity for events filmed in the field. They have provided video transmission for shows such as "Dancing with the Stars", as well as supporting UEFA matches, and athletic events such as the Stockholm Marathon as well as events throughout the continent. Providing connectivity for events such as these requires highly reliable dedicated connections providing very high bandwidths and low latency and packet loss. For example, just one high definition video signal requires 1.5 Gbit/s.

62 European Commission, 2020, Supporting the implementation of CEF2 Digital - SMART 2017/0018; http://publications.europa.eu/resource/cellar/8947e9db-4eda-11ea-aece-01aa75ed71a1.0001.01/DOC_1; accessed on May 2nd 2023

63 See Ecorys, WIK et al (2020) Supporting the implementation of CEF2- SMART 2017/0018

64 PDC, Services & facilities PDC provides; https://www.pdc.kth.se/hpc-services, accessed May 2nd 2023

65 See for example atNorth, which offers HPC as a service from its Kista Science City site, atNorth means More Compute; https://atnorth.com/about/why-atnorth, accessed May 2nd 2023

66 Strube Martins & Wernick, 2021, Regional differences in residential demand for very high bandwidth broadband internet in 2025; https://reader.elsevier.com/reader/sd/pii/S030859612030135X?token=BDB46F6C93555A50DDC5694CC56643A3DBE039EB090194889B7C44D5562E6171281161F604D164BA0658AB6A2CD9EA8A&originRegion=eu-west-1&originCreation=20230502084626; accessed on May 2nd 2023

> "Just one high definition video signal requires 1.5 Gbit/s. Ultra-high-definition requires 12 Gbit/s if uncompressed. 16 wavelengths over a single fibre and achieve 1.6 Tbit/s easily, and above if needed. This should provide capacity levels that meet all reasonable needs for the foreseeable future" - Andreas Langell, CEO of Mobile Links

Ultra-high-definition requires 12 Gbit/s if uncompressed. Andreas Langell, CEO of Mobile Links explains that it may be possible to compress UHD video to around 1 Gbit/s but it is preferable not to do this, mostly because of the complex encoding, especially when short distances are involved.

Dark fibre is the technology of choice for Mobile Links, as it means they can fully control the services they run over fibre and take full advantage of the very high capacities and security it offers. Langell notes that they can run 16 wavelengths over a single fibre and achieve 1.6 Tbit/s easily[67], and above if needed. This should provide capacity levels that meet all reasonable needs for the foreseeable future. Langell says: "We are spoiled in Stockholm. It is quite unique to have one supplier which can provide connectivity at short notice at what can be odd locations like the middle of the street, as we needed for the Stockholm marathon. With fibre, all the communications work as if the camera were in the studio."

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Langell notes that while other technical solutions have to be used when fibre is not available at a filming location, they don't provide the same advantages. For example, satellite can work well when there is a line of sight and simultaneous broadcasting, but is limited in bandwidth, and is charged on a cost-per-minute basis[68], unlike fibre which generally involves fixed charges for unlimited capacity. Meanwhile when using "best effort" networks like mobile, it is necessary to compensate for packet loss, which can cause delay[69]. Mobile Links makes use of 4G connections with bonding from different operators to provide connectivity for news reporters on the street, but Langell notes that it is not suitable for premium content. Full 5G could provide more bandwidth and quality guarantees, but because capacity is constrained on mobile networks, Langell fears that obtaining quality guaranteed network slices offering the necessary capacity is likely to come at certain monetary costs. Microwave links are also used, but not as reliable as fibre.

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67 See also Alhalabi et al., 2022, 1.6 Tbit/s OFDM WDM-PON system employing RSOA as a colorless transmitter; https://assets.researchsquare.com/files/rs-1859091/v1/4576501c-97b3-4855-ba36-861b965ef965.pdf?c=1665519221, accessed May 2nd 2023

68 See also Cooper, 2019, Pros And Cons Of Satellite Internet; https://broadbandnow.com/guides/satellite-internet-pros-and-cons, accessed May 2nd 2023 and https://www.satellitephonereview.com/use-pros-cons/; accessed on May 2nd 2023

69 See also Gevros et al., 2001, Congestion Control Mechanisms and the Best Effort Service Model

Langell considers that Stokab's fibre infrastructure has provided significant benefits for the city as a whole and observes that it is more challenging to obtain fibre in many European cities, where there are multiple operators present at the different filming locations. Another challenge is that when a cooperating broadcast company is a competitor to a telecom operator (being simultaneously active in the media segment) that owns the fibre, they might not offer fibre access on such good terms. **"Fibre should be seen as an essential infrastructure to be provided by a country or city and not as a commercial service," says Langell.**

6.3 Digital healthcare

The Stockholm Region provides healthcare to 2.2m inhabitants. Fredrik Engströmer heads up innovation in the Region of Stockholm. He explains that the Region has been exploring how to support the needs of patients at each step in their healthcare journey from the moment when the patient falls sick to the delivery of care and their ongoing follow-up support with the hospital. As part of an ongoing project, which started in 2021, the Region has been running trials using quality-assured 5 services. The starting point is to provide support at the site of a disaster zone or accident by using 5G to stream video from the ambulance. This involves transmitting from cameras installed inside the ambulance and on ambulance personnel. These images are then transmitted to the Emergency Room, enabling doctors to intervene to advise on early medical interventions. Engströmer observes that this is important particularly in conditions such as stroke, where every minute counts. 5G has also been installed inside Karolinska hospital, which acts as a Hub for innovation training activities for the region. To address aftercare needs, the Region is also engaged in a home care project in which patients with cardiac and other chronic conditions are connected into Karolinska hospital and can be monitored remotely. Engströmer notes that Stokab's network is playing a crucial role in these trials as 5G requires fibre to the base station to fully function. The fibre network also played a crucial role in supporting remote healthcare during the COVID pandemic. Engströmer notes that use of the Region's application for remote medical appointments increased dramatically increased during pandemic. "Video consultations require that people have a good broadband connection at home," he notes.

6.4 Traffic and environmental management

The Stokab fibre network has also played a vital role in supporting the Region's transport system. In a trial where traffic lights were controlled based on prioritisation rather than timing alone, commuting time for buses was cut by 40%, with car journey times also achieving modest improvements. The City has identified 120 crucial traffic lights for prioritisation of public transport and is implementing a platform in preparation for the wider roll-out of the system.

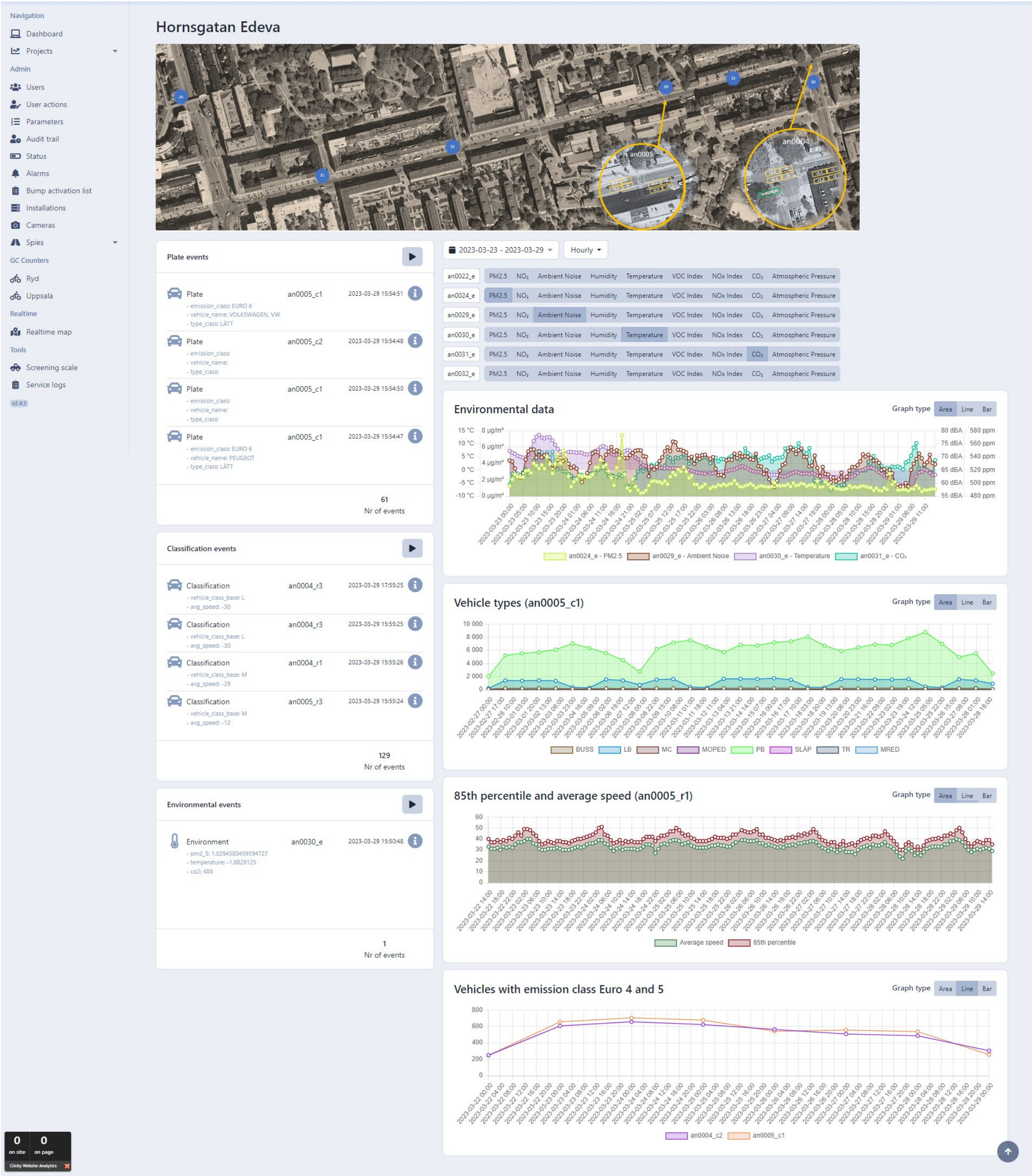
The Region and Stokab are also collaborating with industry and research institutions to support trials of traffic and emissions management. **RI.SE**, a research institute established and owned by the Swedish Government, is at the cutting edge of developments in smart city applications. They are involved in 300+ testbeds across Sweden, both for continuous testing as well as trialling new techniques in science and technology. One of their current projects involves trialling smart city solutions around Hornsgatan street, in the central South side of Stockholm City. In this innovation and climate testbed zone, Stokab has installed fibre backhaul to 14 locations serving other partners in the trial that have installed connected various sensors, including radar and cameras, to capture information about traffic patterns and behaviour. This involves using licence-plate recognition to assess whether the vehicles are complying with traffic regulations such as avoiding the bus lanes, refraining from running on spiked tyres as well as meeting environmental standards on vehicle emissions. Based on the Swedish licence-plate register with personal data excluded in beforehand, it is possible to build a database with information such as the class of vehicle and fuel type. It is also possible to assess speeds and distinguish between different kinds of vehicle based on radar in the 60 GHz band.

Alex Jonsson, a researcher at RI.SE describes the project as a typical city project, which involves a lot of data. A key challenge is to synchronise different data points to produce a common timeline. For example, when measuring noise, it is necessary both to distinguish between different vehicles and detect which direction they are coming from using data captured from various sensors. Another challenge is to access power for the equipment. Dr Jonsson notes that it can be challenging to tap into or share electricity. For example, the fact that electric power feed for street lights normally operate only at night creates limitations. However, Dr Jonsson notes that the creativity for creating connectivity in odd locations has not been a problem and solutions available, as the number of access points are plentiful in the Stockholm City area. “Stokab provides access points and has experience in collaborating with various parts of the City and on projects such as these, which saves a lot of time” he says. For the testbed at Hornsgatan, the project team have installed fibre backhaul, cameras and environmental sensors at 14 locations, and additional trials are planned after the Summer of 2023. Cameras in particular have significant connectivity needs. This can amount to 10-25 Mbit/s per camera depending on the performance needs, and even more bandwidth is required when many cameras are installed and/or have 4k capabilities. Jonsson notes that the video signal output from cameras is usually compressed, but when uncompressed, 1 hour of 4K video could consume 1.3 terabytes corresponding to 6 Gbit/s.

Dr Jonsson notes that they also conducted trials at a site in the North of Stockholm, the Royal Sea Port (Norra Djurgardsstaden). However, there was not as much fibre available there, and this created additional challenges. They needed to use cellular 4G (LTE) modems, but this involved using commercial operators and required additional power for the devices, which was hard to source. “Practically, the options were to use car-type batteries and conceal them somewhat along walkways and in the woods, or to limit the methods and locations for measurement to places where there was connectivity. This meant that measurements could not always be performed in the ideal locations” said Jonsson. “For example, if you can mount a camera and operate radar close to and pointing in parallel with the road elongation, it is possible to carry out complex classifications with many vehicle types, but if you have to conduct the measurements to the side or even across the sidewalk, the measurements are at an angle, which in turn limits the kinds of vehicles and movements that can be classified. Having a lot of fibre connectors everywhere reduces many of these challenges.” RI.SE considers that fibre networks operated by municipalities can be important in supporting research centres and test beds because they do not need to follow the practices of commercial players, which typically increase prices, disallows control over operations as well as the expected output when they have the only fibre available at a given location. In addition to supporting testbeds for Smart City applications, RI.SE notes that fibre from city networks have since used to support third parties for radio and broadcasting transmission in Sweden, enabling the transmission of medical imagery such as X-Rays between hospitals and other sites, assisting law enforcement and fire departments with surveillance needs, and for creating other secondary wired and wireless networks for governmental and commercial operations with special connectivity needs.

Edeva specialises in developing Smart City solutions. One of their inventions is the “actibump”, a dynamic speed bump that lies flat to the road, but lowers to slow traffic when drivers are exceeding speed limits.

Edeva has also been involved in the trials along the Hornsgatan, which is considered to be the most polluted street in Stockholm. Edeva’s applications include environmental sensors, radar to detect movement and licence plate detection and analysis. The following figure provides an example of the kind of data they have been able to gather and analyse in the Hornsgatan testbed.



Not all the applications they support require very high bandwidths. However Edeva's CEO David Eskilsson notes that even when high bandwidths are not required, fibre connections can provide other benefits. For example, environmental sensors do not require high bandwidth, but because they are low power, they can be powered via an ethernet connection out of Stokab's technical cabinets in the field, which can remove the need for alternative power solutions such as solar cells or batteries. Meanwhile, for equipment such as number plate sensors, Edeva has been able to make use of power in Stokab's technical cabinets, connect to the fibre and co-locate their own equipment, giving them control over the service end-to-end. Licence plate processing involves massive amounts of data. At their test bed in Stockholm, Eskilsson notes that around 20,000 vehicles pass each site every day. Because most of the data from number plates is processed at the edge, it is possible to rely on lower bandwidth connections - 10Mbit/s can be sufficient. However, stability of the connection is important, and with fibre, services can be designed differently than in cases where bandwidth is constrained or even affected by electric interference. Eskilsson notes that the additional bandwidth made available through dark fibre could also support future applications involving the processing of data on sound, video and vibrations in the cloud.

7 Lessons from Stockholm's innovation strategy

In this chapter, we examine how the City of Stockholm has established infrastructure and training programmes to instil innovation throughout the organisation. We conclude by considering what lessons can be learned for other regions aspiring to boost their innovation potential. Key findings are that:

- As can be seen through the example of Stokab, dark fibre can provide an important platform to support the innovation ecosystem both on the supply and demand side. National and/or regional administrations should consider whether the market is providing adequate coverage of and access to fibre infrastructure, including the availability of dark fibre. Where this is not the case, administrations could consider strategies to incentivise and, where necessary, support its development
- The City of Stockholm employs a Director of Innovation and has trained key personnel to be innovation leaders. National, regional and local administrations could consider adopting an innovation strategy and training key staff to be innovation leaders.
- Many of the examples of innovation in Stockholm have involved collaboration between the City, Region, academics and industry. National and regional administrations could consider establishing continuous collaboration fora as a means to support the identification of innovative projects which can meet wider societal and business needs.

7.1 Keys to Stockholm's success

The CEO of Stockholm Business Region Staffan Ingvarsson is responsible for attracting capital, entrepreneurs and talent to the Stockholm Region. He notes that a key element in making the city attractive is to build the right infrastructure. Fibre is considered, alongside other critical services such as electricity and public transport to be a **key infrastructure** which is necessary to compete in the global economy and provide a platform for innovation. Ingvarsson notes that "Over the last 20 years we have created an environment where it is easy to start-up and to go global from day 1, because we have connectivity." Other drivers include strong technical skills of the workforce, the presence of key companies such as Ericsson and one of Europe's leading research institutions on life sciences.

Another source of advantage is that the City has adopted an **innovation strategy** and the City Executive office provides support to its companies in achieving accreditation with the global ISO standard in innovation[70]. Overall, more than 40 people, including CEOs from companies owned by the City, have received **innovation training**, with the support

70 This includes concepts and principles of innovation management and its systematic implementation ISO 56000 and ISO 56002. The City of Stockholm is accredited with this standard and some of the administrations such as the city districts Farsta, Hässelby-Vällingby and Norrmalm are working towards it.

of adjunct Prof. Magnus Karlsson of the Royal Institute of Technology who was closely involved in the development of the standard. The training covers eight themes and includes advice on how to govern, assign budgets and set long term goals in a way that will make innovation happen. To support this process, the City employs a Director of Innovation working directly in the CEO's office. Karin Ekdahl Wästberg's task is to support administrations and companies owned by the city in pursuing an innovation agenda. As an example, Ekdahl Wästberg notes that innovation is essential to achieve long term goals such as being climate positive. "We cannot go on as we were because otherwise we will not achieve our goals", she says. "We need to have leadership that enables innovation and a governing system to support innovation."

Another key to its success is the culture of **collaboration.** The City and Region participate in a forum called "Digital futures" together with companies and research centres such as Ericsson and KTH. Engströmer notes that the forum meets every second week to discuss challenges and how to solve them together. "Many projects end up from these continuous discussions," he says. "We are nurturing the ecosystem all the time." Ekdahl Wästberg adds that the City considers its relations with others as a long-term investment, with researchers helping to expand the knowledge-base and business developing suitable products and services. "We need to work with others in business, academia and other parts of the public sector so that we can reach the targets together. For example, we cannot reach the goal of being climate positive by 2030 on our own", she says. As an example, she notes how the City used its public procurement policies to support zero emissions targets in the context of construction work at Slakthusarea. This led to a collaboration between Skanska and Volva to develop an electrified digger, involving industry in the goal to become climate positive by 2030.[71] The innovation zone Hornsgatan provides another example of collaboration, as the City is working with companies involved in the development of sensors and researchers who are focused on data analytics to gain access to real-time data on traffic, emissions, and security. Ekdahl Wästberg notes that they have learnt a lot from the project including through the use of cognitive sensors (microphones), which can detect whether drivers are using winter tyres. She also envisages that similar techniques could be used to listen to water pumps in the City's extensive water system to provide insights for planned maintenance.

Ekdahl Wästberg also notes that citizens are also front-runners when it comes to technology. "Since almost every household is connected, it is possible for citizens to have benefit from digitisation which in turn supports the innovation ecosystem. Actors within the ecosystem are dependent on each other. **Having strong access to dark fibre is important to the whole innovation ecosystem**."

71 Fossil-free contracting – pilot project at Slakthusarea https://vaxer.stockholm/nyheter/2022/12/fossilfri-entreprenad---pilotprojekt-i-slakthusomradet/

7.2 Conclusions

The City of Stockholm's strategy in boosting innovation provides a number of insights that could help other administrations across the EU in contributing to the achievement of the Digital Decade targets and Europe's wider innovation goals.

- The example of Stockholm shows that a truly futureproof network that allows fibre unbundling, i.e. a **point to point fibre network, can enable innovation** in communications technologies as well as supporting applications in a diverse range of fields.
- High Performance Computing, which is critical for the evolution of big data processing[72] as well as **Quantum communications**, which will be essential for the security of networks in a quantum computing environment, **can only be supported over point to point fibre connections**
- Although it is not the only possible solution, **public ownership of dark fibre networks can help to ensure that research facilities and centres of public interest including schools and hospitals are effectively served** with open and future-proof infrastructure. A variety of communication services and applications can then be provided over the top in the open market.
- The wide and growing range of applications for dark fibre – from the creative industries to smart cities to connections for homes and businesses, show that fibre is no longer just a communication infrastructure but an **essential platform for society and the economy.**

72 https://www.sciencedirect.com/science/article/abs/pii/S0167739X18317679