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**Conference Paper**

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# **Cost, performance and energy consumption of 5G fixed wireless access versus pure fiber-based broadband in Sweden**

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## **ABSTRACT**

This work aims to contribute to the debate on the fixed wireless versus fixed line broadband access solutions by focusing on scenarios offering Gbps level broadband access. More specifically, we performed a techno-economic analysis on the cost, performance (in the term of download speed) and energy consumption of optical fiber versus 5G fixed wireless access (FWA) based solutions over a 10-year perspective. The study is based on the case in Sweden in order to achieve one of the Swedish government's 2025 broadband goals that 98% of Swedish households and workplaces should have at least 1 Gbps broadband access. Alongside with the pure fiber-based solution, 3 FWA-based scenarios using existing commercial macro cells, newly installed mmWave small cells, and hybrid macro and small cells, are evaluated. Based on the findings in this work we conclude that: 1) The pure fiber-based solution should be the "default" choice in order to achieve the Swedish government's 2025 broadband goal to reach 98% of Swedish households and workplaces with at least 1 Gbps broadband access; 2) Even though FWA using mmWave small cells is potentially capable of achieving the 1 Gbps @ 98% goal, the trade-off will be the high total cost levels and more energy consumption. In addition, the end user experience is subject to variations of whether and environmental conditions, and the distance to the network antenna; 3) FWA using existing commercial macro cells alone is not capable to reach the 1 Gbps @ 98% goal, despite the estimated relatively low cost. In addition, the estimated energy consumption level is also significantly higher than the pure fiber-based solution. To the best of our knowledge, this is the first-time reported techno-economic study on comparing 5G FWA with pure-fiber-based broadband access.

**KEYWORDS:** 5G, fixed wireless access, fiber broadband, techno-economic analysis

## 1 INTRODUCTION

With the ever-increasing mainly video-oriented content distributions and services, a Gigabit society has been envisioned where, e.g., all the European households should have access to networks offering a download speed of at least 100 Mbps and which can be upgraded to 1 Gbps by 2025<sup>1</sup>. Compared to the EU Sweden has set an even more aggressive broadband goal, of which 98% of the households and workplaces should have access to at least 1 Gbps broadband access by year 2025<sup>2</sup>. In order to achieve these goals, traditionally optical fiber has been regarded as the “default” solution from the backbone network to the “last-mile” broadband access. Nevertheless, with the advent of the 5G era, the “last-mile” solution of Gbps broadband access is being challenged by the emerging 5G technology offering download speed at Gbps level utilizing newly defined spectrum bands below 10 GHz (the so-called midband) and above (the so called mmWave band) (see e.g. Chandramouli et al. 2019).

This work aims to contribute to the debate on the fixed wireless versus fixed line broadband access solutions (see e.g. Izydorek et al. 2019) by focusing on scenarios offering Gbps level broadband access. More specifically, we performed a techno-economic analysis on the cost, performance (in the term of download speed) and energy consumption of optical fiber versus 5G fixed wireless access (FWA) based solutions over a 10-year perspective. The study is based on the case in Sweden in order to achieve one of the Swedish government’s 2025 broadband goals that 98% of Swedish households and workplaces should have at least 1 Gbps broadband access.

Alongside with the pure fiber-based solution, 3 FWA-based scenarios using existing commercial macro cells, newly installed mmWave small cells, and hybrid macro and small cells (Oughton et al. 2019, Oughton et al. 2018), are evaluated, as listed below.

<b>Scenario 1</b>	FWA using existing commercial macro cell sites
<b>Scenario 2</b>	FWA using newly installed mmWave small cells
<b>Scenario 3</b>	Hybrid FWA using existing macro cell sites densified with new small cells
<b>Scenario 4</b>	Pure fiber-based solution

## 2 METHODOLOGY

This study follows the concept of the “access” as a household or workplace being “passed” by fiber, or being within FWA coverage. Accordingly, in this work we consider the deployment and operational cost of fiber or FWA networks, and any cost associated with the end users is not included.

### 2.1 Key parameter estimation

#### 2.1.1 Targeted homes and workplaces

Accordingly to the Swedish Post and Telecom Authority PTS’s broadband availability 2018 statistics<sup>3</sup>, Table 1 shows the calculated total number of households and workplaces at the end of 2018 that are yet to be passed by fiber or covered by 5G FWA to reach the 98% @ 1 Gbps goal. The calculation assumes that the households and workplaces that are located in the most remote part in rural areas will be those that are not targeted. Table 1 also shows the targeted households/workplaces relative to the total number of

<sup>1</sup> EU Policy (2016). *Connectivity for a European Gigabit Society*. <https://ec.europa.eu/digital-single-market/en/policies/improving-connectivity-and-access>.

<sup>2</sup> <https://www.government.se/information-material/2017/03/a-completely-connected-sweden-by-2025--a-broadband-strategy/>

<sup>3</sup> <https://www.pts.se/sv/dokument/rapporter/internet/2019/pts-mobiltacknings--och-bredbandskartlaggning-2018/>

households & workplaces in urban and rural areas, respectively (for the estimation of the area and road length for targeted end users).

*Table 1 Targeted homes and workplaces*

	<b>Total</b>	<b>Urban</b>	<b>Rural</b>
Households & workplaces to be covered	427 304	259 866	167 438
Percentage to the total number		5.7%	31.7%

## 2.1.2 Estimated area and road length for targeted end users

In order to cost the studied technical scenarios, two key parameters are needed: the total area that needs to be covered by FWA for the targeted end users, and the total length of local roads that connect these end users. These two parameters determine the total number of FWA cells, and the total length of newly installed fibers.

### 2.1.2.1 Targeted area

In order to estimate the total area that the targeted end users utilize, we use statistics from the Statistics Sweden (SCB) of the total developed area in Sweden, both in urban and rural areas, as shown in Table 2.

*Table 2 Total developed area in Sweden*

	<b>Total</b>	<b>Urban</b>	<b>Rural</b>
Total Area (km <sup>2</sup> )	11822	4665	7157

In order to estimate the total area that the targeted end users utilize, we use published studies (Marshall 2007) on the population distribution modelling which states that:

- urban land area (A) increases proportionally to population size (P) raised to a power (n), i.e.  $A \propto P^n$

while n is usually at  $\sim 2$ . Accordingly, in this study, we estimate the targeted areas in urban and rural areas with the following treatment:

- for urban areas, the power of n is set at 2;
- for rural areas, since we just consider those already developed areas (occupying just 1.5% of total area in Sweden), we assume that the power distribution still holds, but to a relatively higher degree, and is set at 2.5.

Table 3 shows the estimated total area to cover both for urban and rural areas, using the corresponding statistics in Table 1. Note here that in the estimation, the targeted end users are considered as those that are located in the most remote part of the urban and rural areas, i.e., all the households/workplaces that already have 1 Gbps broadband access or have been passed by fiber are those that are located in the center part of the urban areas, or at the least remote places in rural areas.

*Table 3 Total targeted area*

	<b>Urban</b>	<b>Rural</b>
Targeted area (km <sup>2</sup> )	519	3144

### 2.1.2.2 Targeted road length

According to SCB<sup>4</sup> and the Swedish Transport Administration (Trafikverket)<sup>5</sup>, Table 4 outlines the total local road length in *urban* and *rural* areas in Sweden.

*Table 4 Total local road length connecting permanent households/workplaces in Sweden*

	<b>Urban</b>	<b>Rural</b>
Total road length (km)	46000	66600

In order to estimate the total road length for the targeted end users, we assume the same principle for the road length distribution with population as for the area, i.e., for urban and rural areas, road length increases proportionally to population size (P) raised to a power of  $n$  at 2 and 2.5, for urban and rural areas, respectively. Based on these assumptions, Table 5 shows the corresponding estimated total targeted local road length.

*Table 5 Total targeted local road length*

	<b>Urban</b>	<b>Rural</b>
Targeted road length (km)	5122	29254

### 2.1.3 Existing macro cells to be utilized

In order to evaluate the FWA solution using existing macro cells, the key parameter is the number of existing macro cells that are to be utilized. In doing this, we estimate that for a typical operator in Sweden, the existing commercial macro cells amounts to 8000 according to Analysys Mason (2018). Furthermore, of these 8000 macro cells, ~ 6000 belong to the urban area, while the rest are located in rural areas<sup>6</sup>, as shown in Table 6.

In order to estimate the total number of existing macro cells that are located in areas occupied by the targeted households and workplaces, we adopted the following approach:

- in urban areas, we assume each macro cell cover the same amount of end users, i.e., the number of macro cells scales proportionally to the number of households and workplaces;
- in rural areas, we assume that each macro cell covers the same amount of area, in considering that the coverage of existing mobile networks is prioritized than the performance in rural areas.

Based on these assumptions, we can calculate the total number of existing commercial macro cells that can be used for our targeted end users, as shown in Table 7.

*Table 6 Total number of existing commercial macro cells*

	<b>Total</b>	<b>Urban</b>	<b>Rural</b>
Number of exiting commercial macro cells	8000	6000	2000

*Table 7 Total number of existing commercial macro cells to be utilized*

	<b>Urban</b>	<b>Rural</b>
Number of cells	344	878

<sup>4</sup> [http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START\\_\\_MI\\_\\_MI0803\\_\\_MI0803E/VaglangdKategori/](http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__MI__MI0803__MI0803E/VaglangdKategori/)

<sup>5</sup> <https://www.trafikverket.se/resa-och-trafik/vag/Sveriges-vagnat/>

<sup>6</sup> Reference data source: Swedish Local Fibre Alliance SSNF's macro cell database

## 2.2 Cost modelling

The cost modelling of the studied technical scenarios consists of two parts, i.e., the radio access network (RAN), and fiber deployment.

### 2.2.1 Cost elements for FWA RAN

In this study, cost elements for 5G FWA RAN are based on two case studies in Britain and the Netherlands (Oughton et al. 2019, Oughton et al. 2018). Table 8 and Table 9 outlines the corresponding cost items for the macro cell 5G multicarrier upgrade, and 5G small cells, respectively. Worth note here is that the spectrum costs are not included as the spectrum considered at midband and mmWave band (see section 2.3) is yet to be allocated and auctioned.

*Table 8 Cost elements of macro cell 5G upgrade*

	CAPEX (€)	CAPEX annual change	OPEX annual (€)	OPEX annual change
5G multicarrier BS	46200	-3%	4400	-5%
Additional carrier on current BS	16950	-3%	2000	
Civil works	20300	3%		
Site rental			5650	3%
core upgrade	10% of RAN and backhaul upgrade cost			

*Table 9 Cost elements of 5G small cell*

	CAPEX (€)	CAPEX annual change	OPEX annual (€)	OPEX annual change
Small cell equipment	2800	-3%	400	-3%
Small cell civil works	15000	-3%	2000	
Small cell site rental, urban			5650	
Small cell site rental, rural			2825	
core upgrade	10% of RAN and backhaul upgrade cost			

### 2.2.2 Cost elements for fiber deployment

Table 10 lists the basic cost elements in deploying fiber active optical networks (AON), based on the model developed by RISE in the ESA project OCEAN<sup>7</sup>.

## 2.3 FWA capacity and power consumption

In this study, in order to obtain an indicative performance estimation for technical scenarios involving FWA, a hypothetical spectrum portfolio is envisioned, as shown in Table 11, following the case study in Ericsson's FWA handbook<sup>8</sup>. In Table 11, the expected spectral efficiency, both for a single beam using SU-MIMO and for the sector total using MU-MIMO, are also listed, based on 3GPP's self evaluation study (3GPP 2019).

<sup>7</sup> <https://artes.esa.int/projects/ocean>

<sup>8</sup> Fixed Wireless Access handbook, Ericsson 2019

Based on the spectrum portfolio and the corresponding expected spectral efficiency, we may calculate both single beam and sector downlink capacities in the term of the total throughput, as shown in Table 12. Note here that the single beam throughput determines the maximum end user download speed when the beam capacity is consumed by one end user. On the other hand, the total sector throughput determines the average download speed for all the end users covered by the sector. Note also here is that for macro cells, we just consider carriers at midband and below. For carriers above midband, only small cells are considered, in considering that, on the one hand, in rural areas where the macro cell inter-site-distance (ISD) is large (see section 3.2.2) mmWave signals can not reach all the end users with good signal-to-noise/interference-ratio (SNIR). On the other hand, in urban areas the physical environmental conditions e.g. a building block also limit the reach of mmWave signals despite the relative short macro cell ISD.

In regarding the power consumption, Table 13 listed power parameter values used in this study. For small cells, the parameter value is based on published pre-study on the energy efficiency of 5G small cell networks (Ge et al. 2017). Based on the same principle that the use of MIMO doubles the power consumption, for macro cells we assume that the total power of a 5G macro cell double that of a 4G LTE cell<sup>9</sup>

*Table 10 Cost elements of fiber deployment*

Cost item	CAPEX (€)	Annual change
Cost per M1 of planning cost	0.25	
Cost per M1 for right of passage and other authorizations	0.30	
Cost per M1 of digging works	30.00	3%
% of increase in construction cost due to re-paving	100%	
Cost per M1 of installation works (blowing cable, splicing, measurements)	7.00	
Cost per M1 for material for passive infrastructure	10.00	
Cost per M1 for surveying and public cadastre registration	1.00	
Cost of acquisition or setting up the spaces for network's nodes	10,000	
Cost of network active equipment on the node, AON	20,000	

*Table 11 FWA spectrum portfolio and expected spectral efficiency*

Carrier band	Total Bandwidth (MHz)	Single beam Spectral efficiency, bps/Hz	Sector spectral efficiency MU-MIMO, bps/Hz
LTE band 1 (Below 3 GHz)	20	5	40
LTE band 2 (Below 3 GHz)	20	5	40
Midband (e.g. 3.5 GHz)	50	5	40
Midband (e.g. 3.8 GHz)	50	5	40
mmWave band (e.g. 26 GHz)	200	4	30
mmWave band (e.g. 28 GHz)	200	4	30

<sup>9</sup> <https://artes.esa.int/projects/ocean>

Table 12 Macro and small cell sector downlink capacities

	Carrier bands	Single beam DL throughput (4:1 DL/UL), Gbps	Sector DL throughput (4:1 DL/UL), Gbps
Macro cell	midband and below	0.6	4.8
Small cell	mmWave	1.28	9.6

Table 13 Macro and small cell power

	Macro cell	Small cell
Unit power, watt	15000	1600

### 3 EVALUATION IMPLEMENTATION

In this study, the cost, energy consumption and performance evaluation are carried out for urban and rural areas separately, in regarding the differentiations of geographical and demographical features between them.

#### 3.1 Pure fiber-based solution

For technical scenario 4, i.e., the pure fiber-based solution, the following treatments are taken in implementing the evaluation:

- For urban areas, the installed fiber length is increased by 30% as compared to the total estimated road length in Table 5, by assuming that fiber needs to be installed on both sides of the street roads corresponding to 30% of the total targeted road length in (the last part of) urban areas;
- For rural areas, on the other hand, the increase of the installed fiber length is considered at a significantly lower level at 10%, i.e., fiber just needs to be installed on one side of the road for most of the households or workplaces in rural areas;
- In urban areas, 70% of digging is assumed to take place on paved surfaces (i.e., requiring re-paving of the street/road after digging), while in rural areas, just 30% of digging is assumed needing re-paving.

#### 3.2 FWA solutions

##### 3.2.1 Traffic backhauling using optical fiber

For the three FWA based solutions, in considering the goal to provide the targeted end users with Gbps speed, the general consensus is that traffic back hauling using optical fiber is needed (Oughton et al. 2018).

##### 3.2.2 FWA using macro cells

Apart from the total number of macro cell sites, as shown in Table 7, the other important parameter is the inter-site-distance (ISD), which is estimated according to Table 14. The attentive reader may notice here that for urban areas, we differentiate ISD between city area (in Swedish *tätort* with over 200 inhabitants) and small town (in Swedish *småort* with over 50 but less than 200 inhabitants). For *city area*, the ISD is estimated by the total area divided by the total number of cell sites (by assuming a 5:1 total site ratio between *city area* and *small town* since the total area of *city area* is 5 times more than *small town*). For *small town*, on the other hand, they are usually located outside major cities, and covered by macro cells less densely in a similar way as in rural areas. Accordingly, we set the ISD for *small town* and rural areas at 8.0 and 10.0 km, respectively, using the corresponding typical indicative values in Sweden<sup>10</sup>. Note here that in Table 14 the average number of households/workplaces covered by each cell is also listed. This parameter

<sup>10</sup> Reference data source: Swedish Local Fibre Alliance SSNF's macro cell database

is used in the evaluation of the average download speed that the FWA network can provide to the covered end users.

*Table 14 Macro cell parameters*

	<b>Inter site distance (ISD), km</b>	<b>Number of sites</b>	<b>Average number of end users per cell</b>
City area	1.3	287	756
Small town	8.0	57	756
Rural	10.0	878	191

Once the macro cell ISD is determined, the corresponding fiber backhaul cost can be calculated (according to the fiber deployment model shown in Table 10). In the calculation of the total fiber backhaul cost, due to possible route curving between cell sites the installed total fiber length is assumed to be increased by 50% for *city area*, 20% for *small town*, and no increase for rural areas of the total macro cell ISD, respectively. Furthermore, all the digging for building the fiber backhaul network is assumed requiring re-paving in urban areas, and 70% of that requiring re-paving in rural areas, respectively.

### 3.2.3 FWA using small cells

For FWA using small cells, the key parameter is the maximum coverage of a small cell, which is set at 0.20 km (Oughton et al. 2019). This results in an ISD of 0.34 km. The total number of small cells required is the ratio of the total targeted area (as shown in Table 3) divided by the coverage area of each small cell, as shown in Table 15.

Based on the ISD and the total number of small cells, the total length of fiber required for the data traffic back hauling can be calculated. Note here that in contrast to the macro cell scenario, no extra increase of fiber length is envisioned due to the short ISD. Furthermore, all the digging for building the fiber backhaul network is assumed requiring re-paving in urban areas, and 70% of that requiring re-paving in rural areas, respectively. In addition, the site rental cost is assumed to be 50% lower in rural areas than in urban areas.

Note here that in Table 15 the average number of households/workplaces covered by each cell is also listed. This parameter is used in the evaluation of the average download speed that each end user can expect. One can see that while in urban areas each small cell covers an average of 52 households/workplaces, in rural areas each small cell just covers 6 households/workplaces.

*Table 15 Small cell parameters*

	<b>Inter site distance (ISD), km</b>	<b>Number of sites</b>	<b>Average number of end users per cell</b>
Urban	0.34	4998	52
Rural	0.34	30254	6

### 3.2.4 FWA hybrid scenario

For the hybrid scenario, the total cost is evaluated with the following considerations:

- The total site rental cost for small cells is deducted by the total number of macro cell sites, as those small cells targeting end users close to the macro cell site are envisioned to share the same site with the existing macro cells;
- The total fiber backhaul network cost is determined by the small cell network, as more fiber is needed to connect all the small cells.

### 3.3 OPEX and total cost

In this study, apart from the total one-time investment, CAPEX, we also evaluate the envisioned operational cost OPEX that consists of the following 3 parts:

1. Energy consumption;
2. Equipment and network node maintenance cost;
3. FWA macro/small cell site rental cost.

In order to obtain a full picture of the cost, we evaluate the total cost of CAPEX and OPEX over a 10-year period of time. In the calculation of total OPEX, the cost items are adjusted according to their annual change rates as shown in Table 8 and Table 9. In addition, in calculating the CAPEX, the deployment of the studied networks is assumed to be carried out over 5 years. Accordingly the cost items (equipment and civil work) are also adjusted over 5 years using the corresponding annual cost change rates as shown in Table 8 and Table 9. Moreover, in converting the total energy (in the term of electricity) consumption into monetary values, a rate of 1.09 SEK/kWh (corresponding to 0.1 €/kWh) is used.

## 4 RESULTS AND DISCUSSIONS

The evaluation on the 4 studied technical scenarios are carried out in regarding:

1. CAPEX and OPEX;
2. Total energy consumption;
3. FWA indicative downlink speed.

Table 16 - Table 27 summarize the evaluation results, which are also illustrated by Figure 1 - Figure 12. Note that in the calculations, a conversion rate of 10.9 from € to SEK is used for the parameter values in Table 8 - Table 10.

### 4.1 CAPEX and OPEX

As shown by Table 16 - Table 23 and illustrated by Figure 1 - Figure 8, in regarding the one-time investment CAPEX, the pure fiber-based approach is at the highest level, while FWA using existing macro cells is at the lowest level, followed by FWA using small cells. The hybrid scenario using both macro and small cells is the most expensive among the FWA based approaches.

In regarding the OPEX, not surprisingly, the pure fiber-based solution has significantly lower OPEX than the other FWA based solutions. Moreover, the two FWA solutions using small cells have dramatically increased operational cost, which is mainly attributed to the maintenance cost of the large number of small cells required.

In regarding the total cost over a 10-year period of time, we can see that on the one hand, FWA solutions using small cells will incur the highest total cost. On the other hand, FWA using macro cells will incur the lowest total cost, at levels around 50% of the total cost of the pure fiber-based approach.

### 4.2 Total energy consumption

As shown by Table 24 - Table 25 and illustrated by Figure 9 - Figure 10, we see that for the total energy consumption (in the term of the total consumed electricity) over 10 years, FWA solutions have significantly higher levels of energy consumption than the pure fiber-based approach, especially for the scenarios using small cells due to the large number of them. Besides, even for the FWA using only macro cells, the total power consumption is expected to be over 7 times and 4 times higher than the pure-fiber based approach in urban and rural areas, respectively.

### 4.3 Average end-user speed

Table 26 - Table 27 and Figure 11 - Figure 12 show the estimated average downlink speed each targeted household/workplace can expect for the 3 FWA based solutions, using the envisioned hypothetical spectrum portfolio and the corresponding expected downlink cell capacities shown in Table 11 and Table 12, respectively. Note here that, rather than mobile broadband applications where an operator usually assumes a temporal average factor, or the so-called overbooking factor of e.g. 50 (Oughton et al. 2018) in the evaluation of the average end-user speed, it's apparently more appropriate to use the real average speed each end user can get *at the same time* to evaluate the FWA performance. This is because for fixed broadband access the end-user behavior is expected to follow a similar pattern, i.e., for workplaces, the peak traffic hours are obviously during the daily working time, while at homes people are expected to consume most of the traffic during the early night hours after people have gone home, *at the same time*. From Table 26 - Table 27 and Figure 11 - Figure 12, we can see clearly that:

1. compared to the “default” (symmetric) Gbps level end-user speed for the pure fiber-based solution, the expected average download speed for FWA based solutions is very much limited, particularly for the FWA solution using only macro cells in urban areas where the total number of households/workplaces covered by one cell becomes relatively large (see Table 14). More specifically, the average end-user download speed using only existing macro cells can be expected to reach only 19 Mbps and 76 Mbps in urban and rural areas, respectively. These expected download speeds are far away from the 1 Gbps goal, even if the operator can double or acquire even more midband spectrum than the hypothetical spectrum portfolio in Table 11. Furthermore, one may argue that mmWave band can also be used in the macro cell solution particularly in *city* areas where the ISD is at 1.3 km (see Table 14). Even so, from Table 12 one can see that this will increase the capacity by 200% from 19 Mbps to 57 Mbps in these (*city*) areas, still far away from the 1 Gbps goal;
2. For FWA solutions using small cells, due to the short coverage range (200 m assumed in this study), and hence significantly reduced number of end users covered by each cell (see Table 15), the expected average end-user download speed can reach the level slightly above 550 Mbps in urban areas, and beyond 1 Gbps in rural areas (in fact just 2 end users are covered by a small cell sector, hence each end user can get the full capacity of a small cell beam). Apparently, by doubling the mmWave spectrum shown in Table 11, even in urban areas FWA using small cells has the potential to provide the targeted households/workplaces with 1 Gbps broadband access.

Nevertheless, it should be noted that for FWA solutions:

- The upload speed is usually significantly lower than the download speed, e.g., even if the DL/UL spectral occupation is 5:1, the upload speed is expected to be significantly lower than 1/5 of the down speed, due to the lower transmitting power of the user equipment;
- FWA speed varies with physical environmental conditions e.g. forest and building blocks, and the performance can also be affected by bad weather conditions e.g. heavy fog, rain etc.;
- FWA end-user speed varies also with the distance to the FWA cell antenna, particularly for macro cells in *small town* and rural areas where the ISD is large.

Table 16 CAPEX per user, urban

	FWA macro cell	FWA small cell	FWA hybrid	Fiber
Total, kSEK	6.16	10.26	12.78	20.72
FWA RAN, kSEK	2.42	4.46	6.98	
Fiber backhaul, kSEK	3.74	5.80	5.80	20.72

Table 17 CAPEX per user, rural

	FWA macro cell	FWA small cell	FWA hybrid	Fiber
Total, kSEK	54.69	93.05	102.92	128.43
FWA RAN, kSEK	12.27	42.44	52.31	
Fiber backhaul, kSEK	42.42	50.61	50.61	128.43

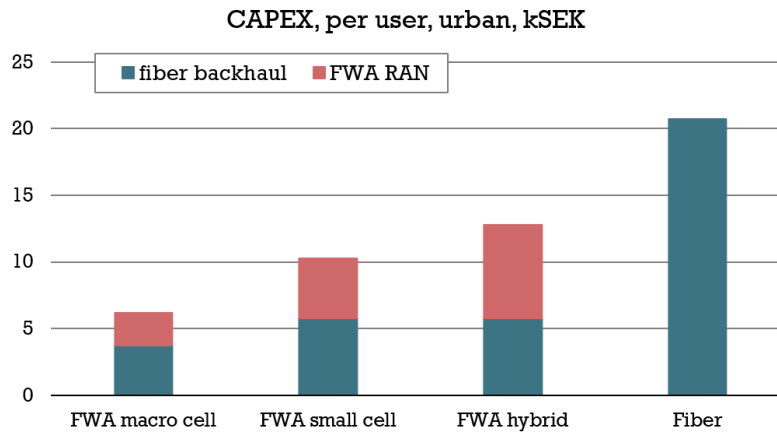


Figure 1 CAPEX per household/workplace, urban area

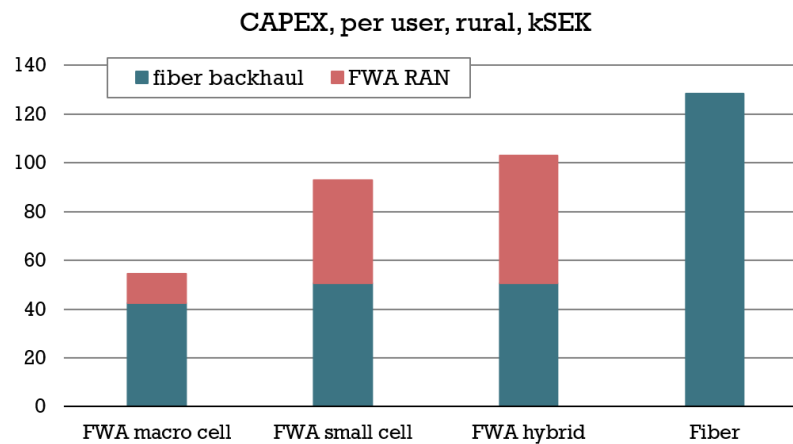


Figure 2 CAPEX per household/workplace, rural area

Table 18 Total CAPEX, urban

	FWA macro cell	FWA small cell	FWA hybrid	Fiber
Total, mSEK	1601	2665	3319	5384
FWA RAN, mSEK	629	1159	1813	
Fiber backhaul, mSEK	972	1506	1506	5384

Table 19 Total CAPEX, rural

	FWA macro cell	FWA small cell	FWA hybrid	Fiber
Total, mSEK	9158	15580	17233	21504
FWA RAN, mSEK	2055	7106	8759	
Fiber backhaul, mSEK	7103	8474	8474	21504

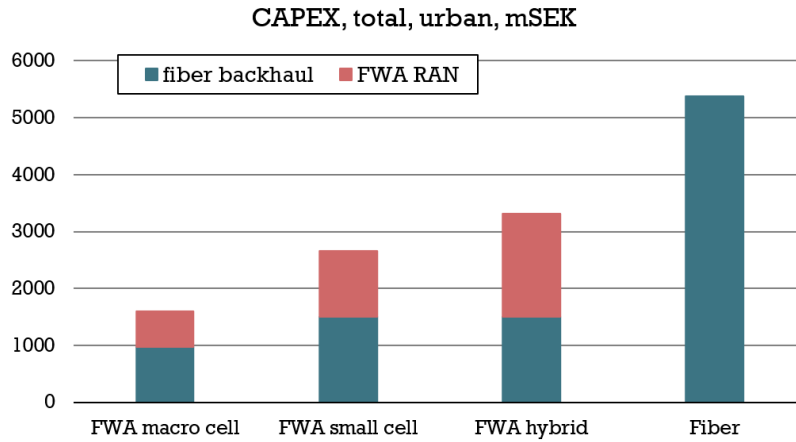


Figure 3 Total CAPEX, urban area

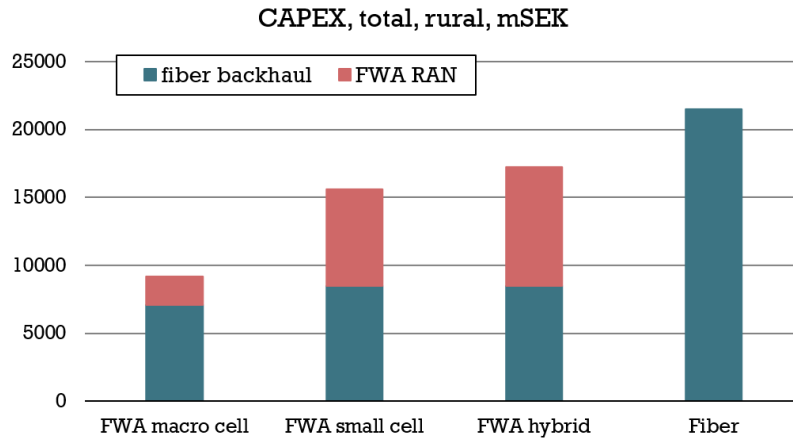


Figure 4 Total CAPEX, rural area

Table 20 OPEX per user per month, urban

	<b>FWA macro cell</b>	<b>FWA small cell</b>	<b>FWA hybrid</b>	<b>Fiber</b>
Total, SEK	30.9	129.3	150.8	3.5

Table 21 OPEX per user month, rural

	<b>FWA macro cell</b>	<b>FWA small cell</b>	<b>FWA hybrid</b>	<b>Fiber</b>
Total, SEK	127.4	637.7	739.7	26.2

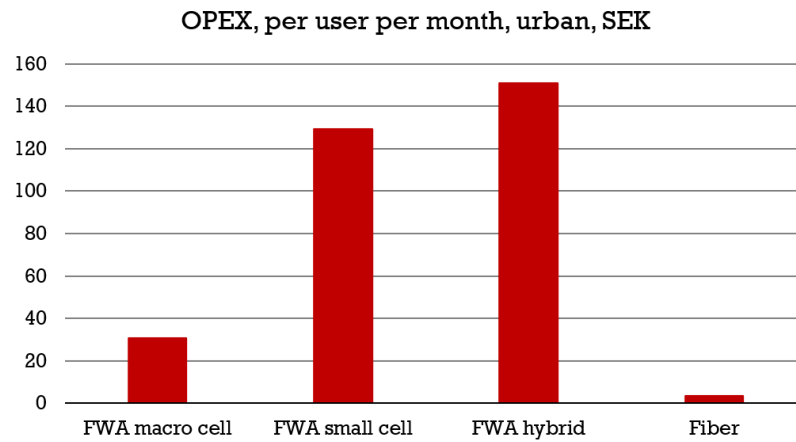


Figure 5 OPEX per household/workplace per month, urban area

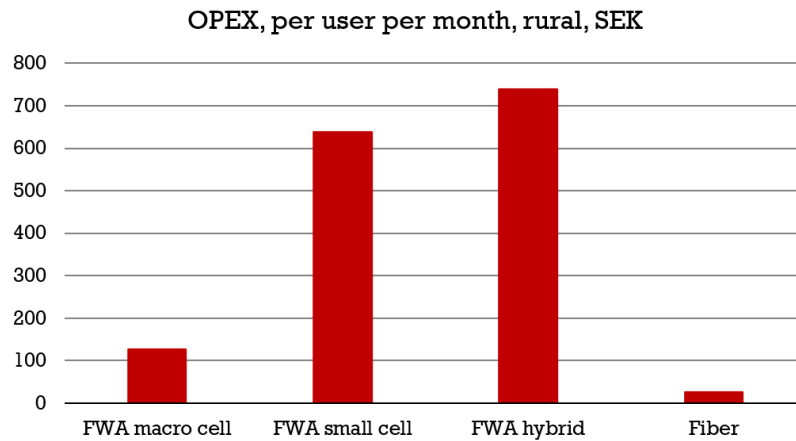


Figure 6 OPEX per household/workplace per month, rural area

Table 22 Total CAPEX and OPEX over 10 years, urban

	FWA macro cell	FWA small cell	FWA hybrid	Fiber
Total, mSEK	2566	6697	8023	5493
CAPEX, mSEK	1602	2665	3319	5384
OPEX, mSEK	964	4032	4704	109

Table 23 Total CAPEX and OPEX over 10 years, rural

	FWA macro cell	FWA small cell	FWA hybrid	Fiber
Total, mSEK	11718	28394	32096	22030
CAPEX, mSEK	9158	15580	17233	21504
OPEX, mSEK	2560	12814	14863	526

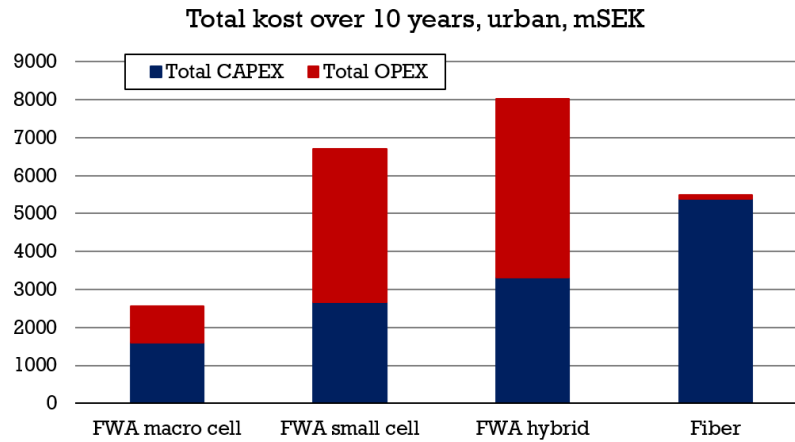


Figure 7 Total CAPEX and OPEX over 10 years, urban area

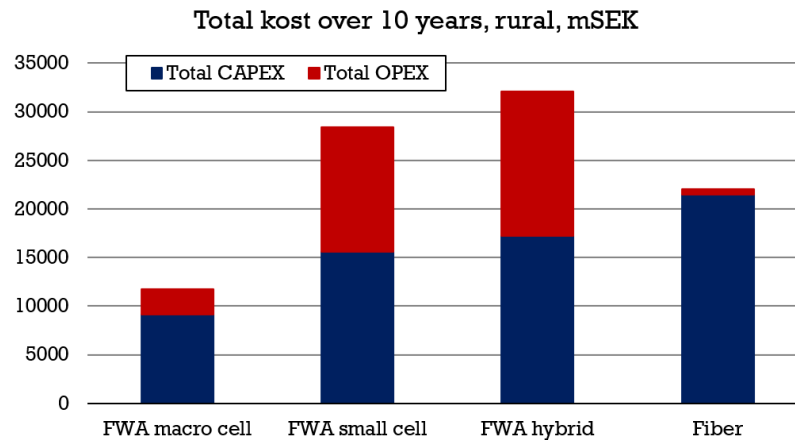


Figure 8 Total CAPEX and OPEX over 10 years, rural area

Table 24 Total energy consumption over 10 years, urban

	<b>FWA macro cell</b>	<b>FWA small cell</b>	<b>FWA hybrid</b>	<b>Fiber</b>
Total, m-kWh	464	707	1113	60

Table 25 Total energy consumption over 10 years, rural

	<b>FWA macro cell</b>	<b>FWA small cell</b>	<b>FWA hybrid</b>	<b>Fiber</b>
Total, m-kWh	1238	2186	3284	290

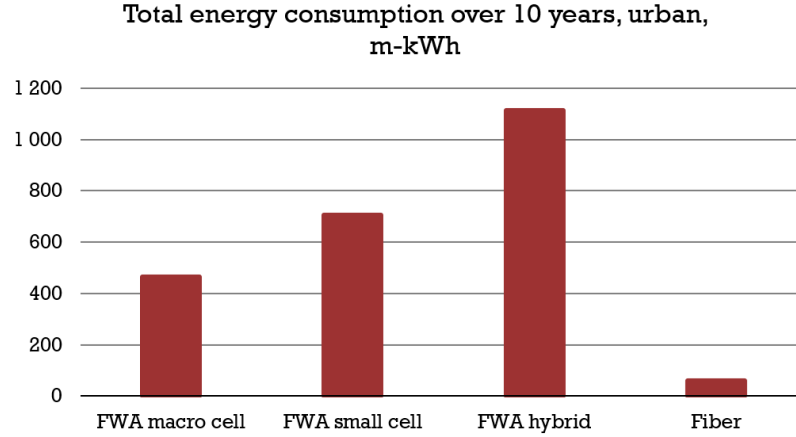


Figure 9 Total energy consumption over 10 years, urban area

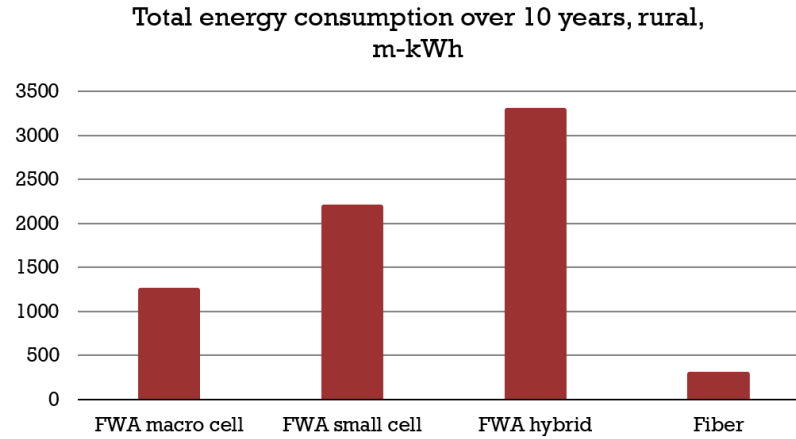


Figure 10 Total energy consumption over 10 years, rural area

Table 26 FWA downlink speed per user, urban

	<b>FWA macro cell</b>	<b>FWA small cell</b>	<b>FWA hybrid</b>
Mbps	19	554	573

Table 27 FWA downlink speed per user, rural

	<b>FWA macro cell</b>	<b>FWA small cell</b>	<b>FWA hybrid</b>
Mbps	76	1280	1356

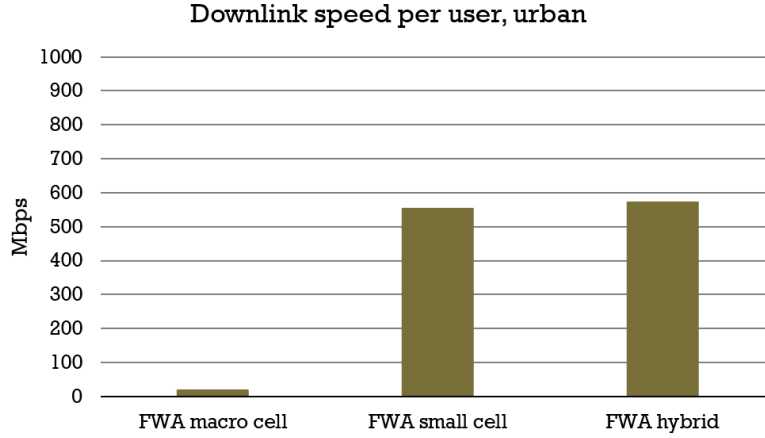


Figure 11 FWA downlink speed per user, urban area

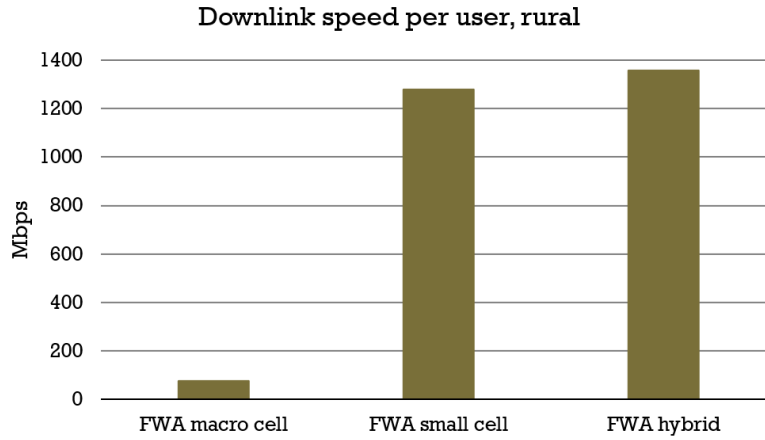


Figure 12 FWA downlink speed per user, rural area

## 5 SUMMARY AND CONCLUSIONS

This study performs an analysis on the cost, energy consumption and performance (in the term of download speed) of optical fiber versus 5G FWA-based solutions in order to achieve one of the Swedish government's 2025 broadband goals that 98% of Swedish households and workplaces should have at least 1 Gbps broadband access. Alongside with the pure fiber-based solution, 3 FWA-based scenarios using existing commercial macro cells, newly installed mmWave small cells, and hybrid macro and small cells, are evaluated. From this study, we find that:

- FWA using existing commercial macro cells is estimated to have the lowest total cost over 10 years. However, the average download speed each targeted households/workplace can expect is far below the 1 Gbps goal, and this download speed gap is not expected to be bridged even if the operator acquires more midband spectrum, or even add mmWave band to the existing macro cells;
- FWA solutions using mmWave small cells can, on the one hand, can support the targeted households/workplaces in rural areas with over 1 Gbps download speed, and potentially can support the targeted households/workplaces even in urban areas with 1 Gbps broadband access by doubling the mmWave spectrum (which will incur more cost and more energy consumption in addition to those calculated in this study). On the other hand, due to high operational cost, FWA solutions using small cells are expected to incur the highest total cost over 10 years, particularly for the FWA hybrid scenario using existing macro cells densified with newly installed mmWave small cells. In

addition, FWA using small cells will be more energy consumptive, due to the large number of small cells that need to be deployed;

- FWA solutions have significantly higher levels of energy consumption than the pure fiber-based solution. In addition, the upload speed is usually significantly lower than the download speed, and can vary with whether and physical environmental conditions e.g. heavy fog, rain, forest and building blocks etc. Moreover, the average end-user speed does not necessarily mean the guaranteed access speed for all the FWA covered households/workplaces, since the network performance varies with the distance to the FWA cell antennas, particularly for macro cells in small town and rural areas where the inter-site-distance is large.

Based on these findings, we conclude that:

1. The pure fiber-based solution should be the “default” choice in order to achieve the government’s 2025 broadband goal to reach 98% of Swedish households and workplaces with at least 1 Gbps broadband access;
2. Even though FWA using mmWave small cells is potentially capable of achieving the 1 Gbps @ 98% goal, the trade-off will be the high total cost levels and more energy consumption. In addition, the end user experience is subject to variations of whether and environmental conditions, and the distance to the network antenna;
3. FWA using existing commercial macro cells alone is not capable to reach the 1 Gbps @ 98% goal, despite the estimated relatively low cost. In addition, the estimated energy consumption level is also significantly higher than the pure fiber-based solution.

## REFERENCES

- Devaki Chandramouli, Rainer Liebhart and Juho Pirskanen (2019). 5G for the Connected World. Wiley Telecom.
- Izydorek, Z., Gravey, A., & Tadayoni, R. (2019). How, when and where can Fixed Wireless Access compete with FTTH? In 2019 European Conference on Networks and Communications (EuCNC) (pp. 63-68).
- Oughton, E.J., Frias, Z., van der Gaast, S., and van der Berg, R. (2019) Assessing the capacity, coverage and cost of 5G infrastructure strategies: Analysis of The Netherlands. *Telematics and Informatics* 37 (2019) 50-69.
- Oughton, E.J., Frias, Z. (2018). The cost, coverage and rollout implications of 5G infrastructure in Britain. *Telecommunications Policy* 42 (2018) 636–652.
- Julian D. Marshall, *Urban Studies*, Vol. 44, No. 10, 1889–1904, September 2007, "Urban Land Area and Population Growth: A New Scaling Relationship for Metropolitan Expansion"
- Analysys Mason (2018). Critical communications for public protection and disaster relief. <https://blogg.telia.se/app/uploads/sites/4/2018/03/Kostnadsanalys-BI%C3%A5ljusn%C3%A4t.pdf>
- 3GPP (2019). Study on self evaluation towards IMT-2020 submission. 3GPP TR 37.910 V16.0.0
- Xiaohu Ge, Jing Yang, Hamid Gharavi, Yang Sun (2017). Energy Efficiency Challenges of 5G Small Cell Networks. *IEEE Communications Magazine*, Volume: 55 , Issue: 5