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Considerations on the energy consumption of Fixed Wireless Access (FWA) operation.

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1 Introduction

The world of information and communications technologies (ICT) has changed rapidly in the last decade. The internet and its surrounding technologies became the most commonly used communication medium in people's personal and working lives. It is critical for a vast range of services – gathering information, communication and entertainment are only the main functions.

The importance of internet communication and internet access has increased significantly in recent months. Due to the high number of people who had to work from their home offices during the Corona pandemic or the observed increase in the use of social media and streaming services, the demands on internet access also increased.

Key to access the internet and to use its services are broadband access networks. In the previous main study, the wired technologies DSL, DOCSIS and FTTB infrastructures were considered. In this extension, Fixed Wireless Access (FWA) is now considered in more detail.

Despite the availability of advanced access technologies, physical roll-out is still lagging behind in 2021. While there is now a strong focus on FTTB/H technologies, the roll-out requires significant funding and resources. Therefore, other or transitional technologies continue to be developed and considered.

Fixed Wireless Access is one such technology. However, it is not correct to speak of a technology. Fixed Wireless Access is more of a concept or a network structure. After all, fixed wireless access means nothing other than realising the house connection of a wired infrastructure through a radio system. Only the last few metres are bridged by radio and there is no need for an expensive house connection. This is expected to initially reduce or postpone costs and shorten the time to market. The radio technologies used vary from WLAN technologies and proprietary systems to 5G.

Here, too, data rates of up to several GBit/s are possible on the radio link, as long as the right radio technology and the best possible propagation conditions are taken into account.

In view of the ever-increasing effects of climate change, however, FWA must also be considered from an energy perspective. In particular, the electrical energy demand during operation must be taken into account.

This work is a first exemplary consideration of the energy demand of FWA infrastructures and does not claim to be complete. Rather, this work is intended to contribute to a discussion on the energy contribution of the telecommunications industry as a whole and of telecommunications networks in particular to climate protection.

2 Scope

The focus of this extension is again on the access network. The core networks and the regional networks are not considered.

The access network connects each subscriber to their immediate service provider. In contrast to the main study, where the access network ended at the passive network termination on the customer side (see Figure 1), in the case of FWA the access network terminates with the active radio station (see Figure 2).

The active network termination on the operator side and the first connection in the direction of the core network are also part of the access network.

The needed active customer premises equipment (FWA radio connection) will be examined additionally.

The following components are part of the examination:

FWA access network

- Active FWA Access Unit
- Central office equipment
- Connection into the core network
- Air conditioning

FTTH customer premises equipment

- FWA Unit with router function and wired connection

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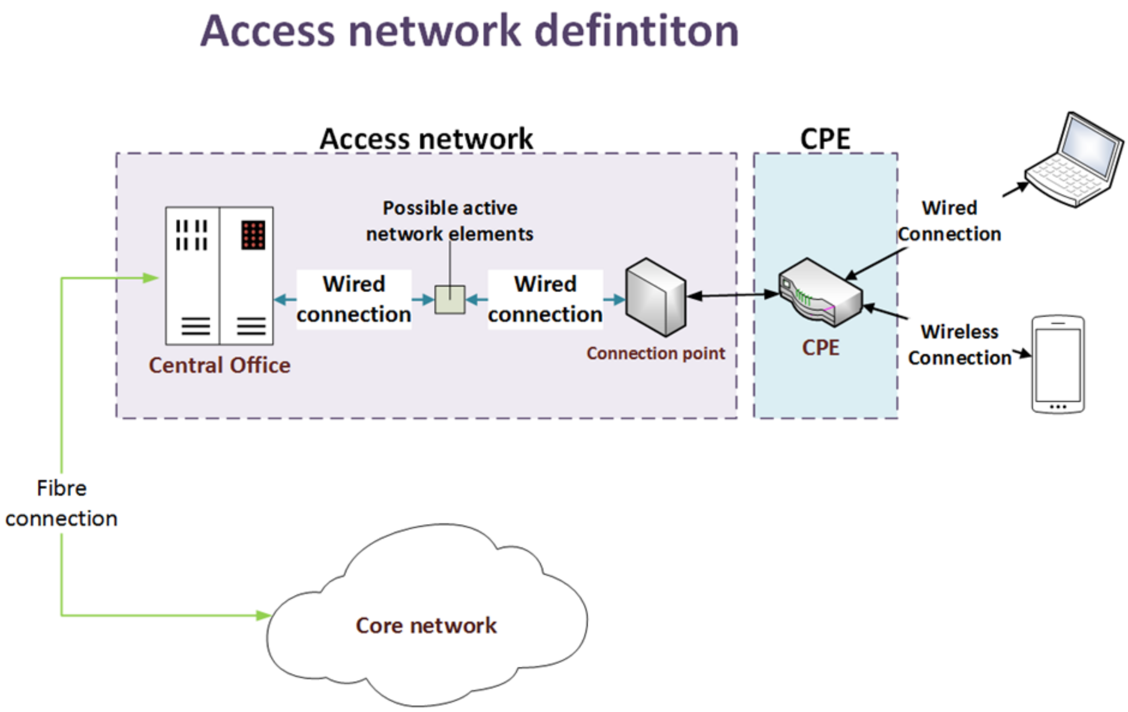

Figure 1: Access network definition as in the main study.

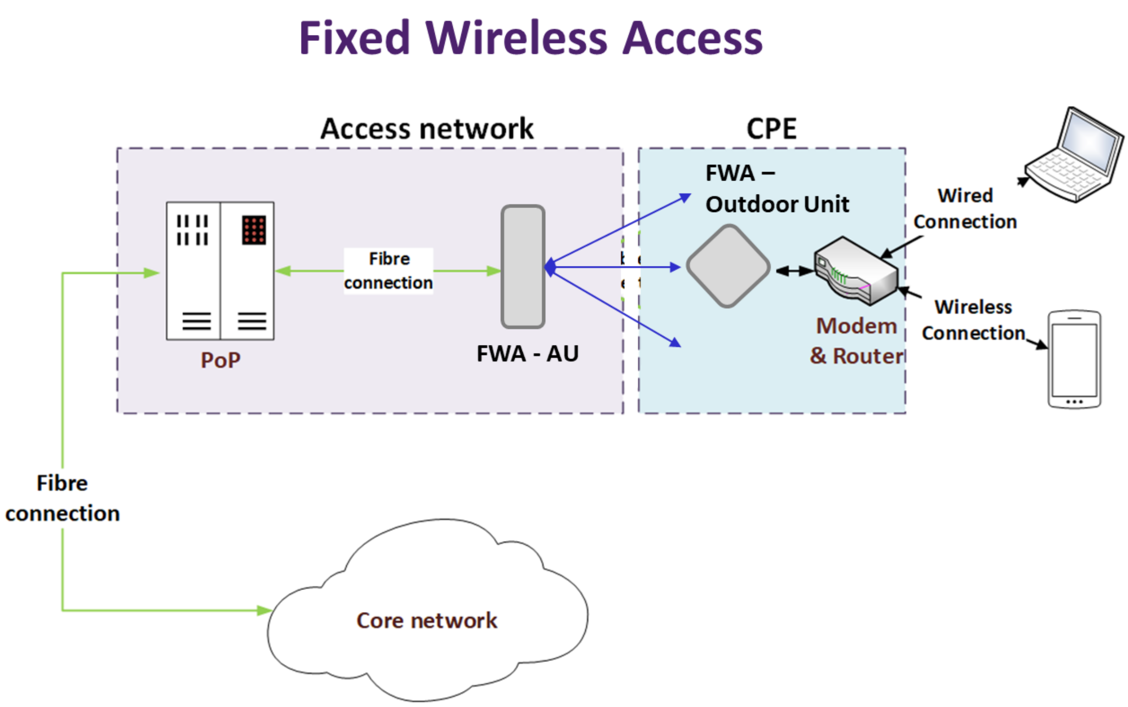

Figure 2: Access network definition for FWA. (FWA – AU: radio access unit)

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3 General Approach

This survey is a first consideration on the energy/power consumption of Fixed Wireless Access. As in the main study, the aim is not to generate energy consumption values for single devices of different manufacturers or normalized values per single port or user. It rather evaluates the overall energy consumption for a Fixed Wireless Access infrastructure at a realistic rollout in a model region. For this purpose, an actual region is selected, which represents a typical rural to urban settlement structure in Germany.

The first step is to reach as many subscribers as possible. Compared to the main study, a 100% roll-out does not seem realistic here. Due to the settlement structure, there are various individual locations where the costs of an FTTB/H house connection are no longer significant in relation to the costs of the fibre optic feed and thus make a transitional solution with FWA superfluous.

In the next step, the individual data rate per subscriber is considered - starting at 50 MBit/s (to improve comparability with the main study), through 250 MBit/s and 500 MBit/s, up to 1 GBit/s per subscriber without overbooking.

Both steps lead to a topology determination and thus to a quantitative estimation of the active network elements and their secondary systems. In combination with data on the energy/power consumption of the individual network element, an overall energy/power consumption can be estimated for FWA. This method creates a supply related energy/power consumption. In other words, “How much electrical energy is needed by FWA to provide a specific data rate for as many subscribers as possible in the specified area?”.

4 Data basis

According to the general approach, the energy/power consumption of FWA will be examined for a specific model region. Therefore, a data basis is needed, which allows a geographical referenced and statistical analysis.

The model region is the same as in the main study and covers rural to urban settlement structures and includes business parks as well.

The model region lies within North Rhine-Westphalia (Germany) and consists of six municipalities. Because of non-disclosure agreements, the model region had to be anonymised and the municipalities are now named A to F (see Figure 3). This also applies to other internal information, which were provided by different companies.

Model region	Population (approx.)	Area (approx.) [km²]	Population density (approx.) [Pop/km²]
A	6500	40	163
B	11800	40	295
C	13700	49	280
D	9400	52	181
E	7200	59	122
F	8100	58	140
total	56700	298	190

Figure 3: The table shows data of the model region and its six municipalities

All municipalities are comparatively small in their population and spatial expansion. However, these regions are typical for the German settlement structures outside the metropolitan areas like Berlin, Frankfurt, Cologne or the Ruhr valley. The population density differs between approx. 122 and 295 people per km² (see Figure 3). As Figure 4 shows, the population density inside the regions fluctuates considerably. In order to this, the population density in the inner cities is partly higher than the table in Figure 3 shows. In the outskirts the population density drops under the mentioned number.

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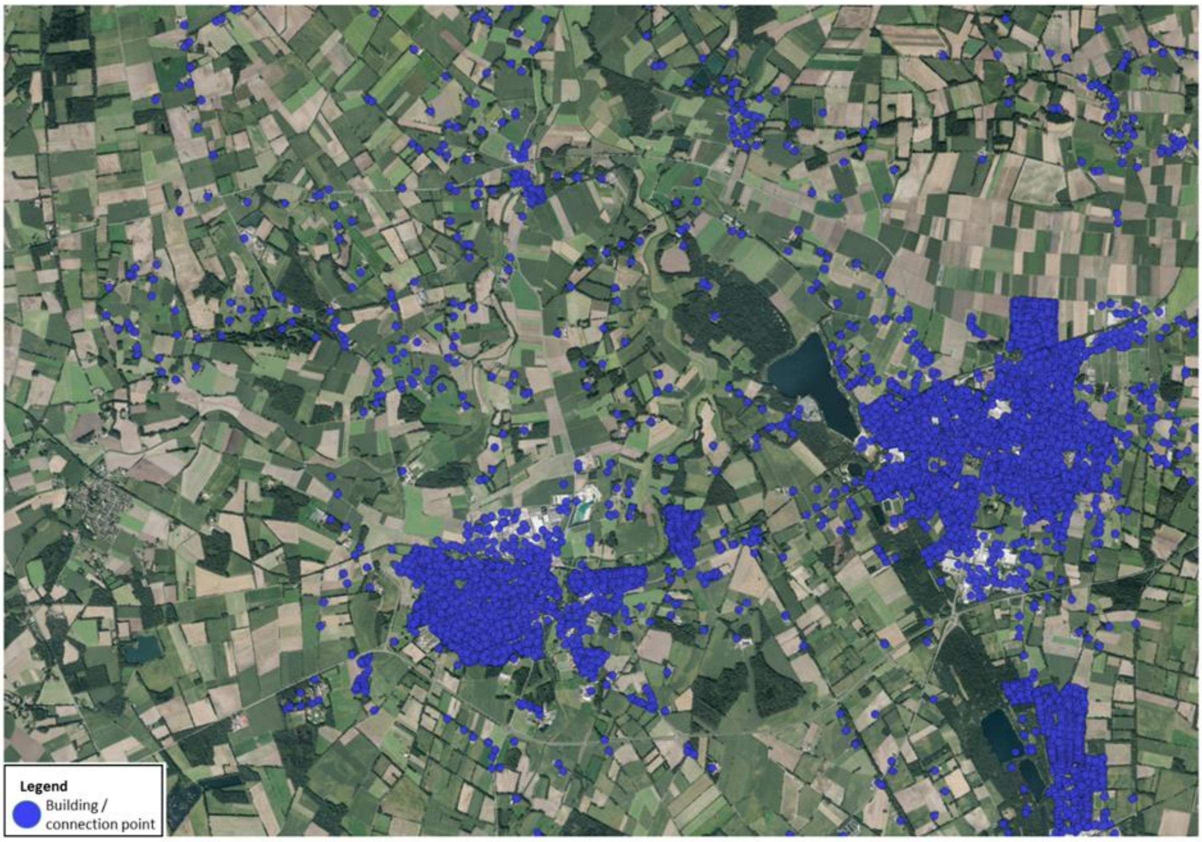

Figure 4: Example of the various population densities in the model region.

Within the model region approx. 26,000 households, companies, public administration etc. – further on referred to as subscribers – exist in 17,000 properties. Approximately 16,000 of these properties and nearly all 26,000 subscribers have been geographically referenced (see Figure 4). For all these 17,000 properties, the outlines and location of all buildings were determined. In addition, about 4,500 roads with almost 4,000 intersections were georeferenced.

These geographical data form the basis for all further considerations.

Since this consideration of FWA is a temporary substitute for the house connection of an FTTB infrastructure, a new roll out of the necessary fibre infrastructure in the area of the access network is also assumed and no existing infrastructure is taken into account.

5 Modelling

As already briefly described, the energy demand is to be determined on the basis of a realistic roll-out of an FWA infrastructure in the model region. To do this, the basic topology of an FWA infrastructure must first be defined.

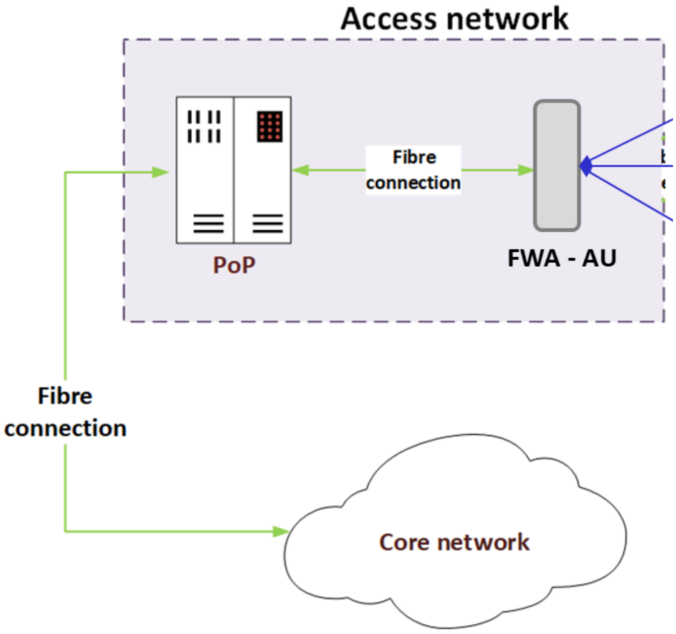

Figure 5: Topology of the FWA access network.

As Figure 5 shows, the FWA infrastructure consists of two active components, the FWA Access Unit – i.e. the radio unit in the area in front of a subscriber's building – and the network termination in the PoP (here the first hop into the core network and air conditioning are also taken into account). Each FWA-AU is connected to the PoP via a fibre optic link.

First, the number of FWA-AUs is determined based on the geographical location of the subscribers. This in turn determines the number and size of the PoPs.

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5.1 Determination of the Access Units

Basic assumptions:

- Small sites with point to multipoint technology
- FWA sites are located along the streets
- FWA equipment should be mounted in an elevated position to minimise vandalism and radio shadowing, e.g. by vegetation or smaller buildings (garages etc.)
- FWA AUs need energy supply
- Line of sight (for high data rates)

Considering the basic assumptions, street lamps appear to be a suitable location for the FWA-AUs. They are located along the streets (in German residential areas approx. every 50 m) and allow for elevated mounting. A power supply is also available at all street lamps. However, it would have to be clarified whether the power supply is permanently connected to each lamppost - i.e. switched on site - or not.

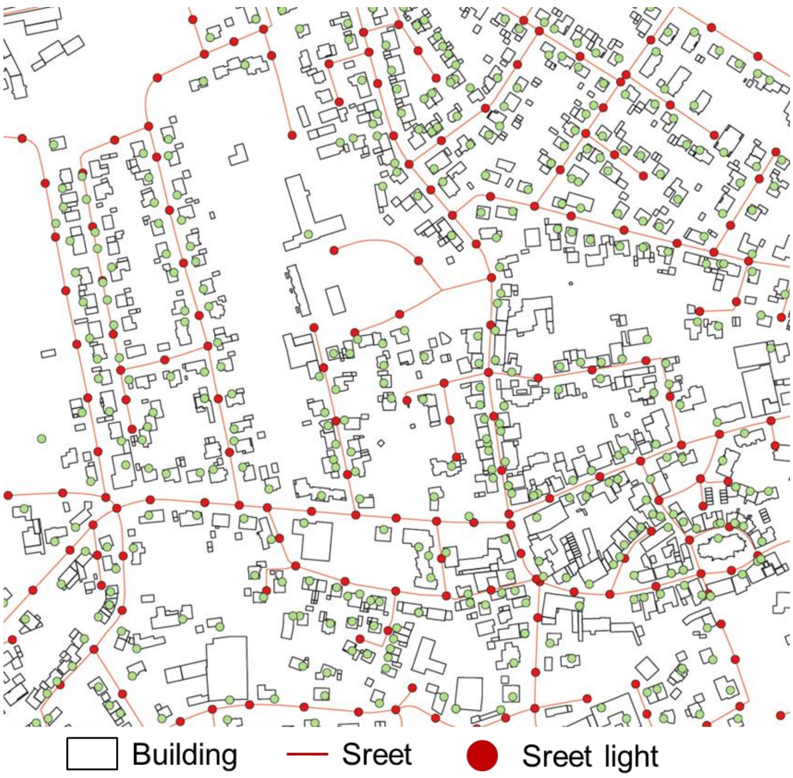

Figure 6: Grid of streetlights at 50 metre intervals.

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As no geo-referenced data on the location of street lights was available, a 50 m grid with potential FWA locations was created along all streets in the model region. This is shown in Figure 6, the streets are marked as red lines and the 50 m grid for the potential FWA locations are marked as red dots. The shape and location of the buildings is indicated by black outlines.

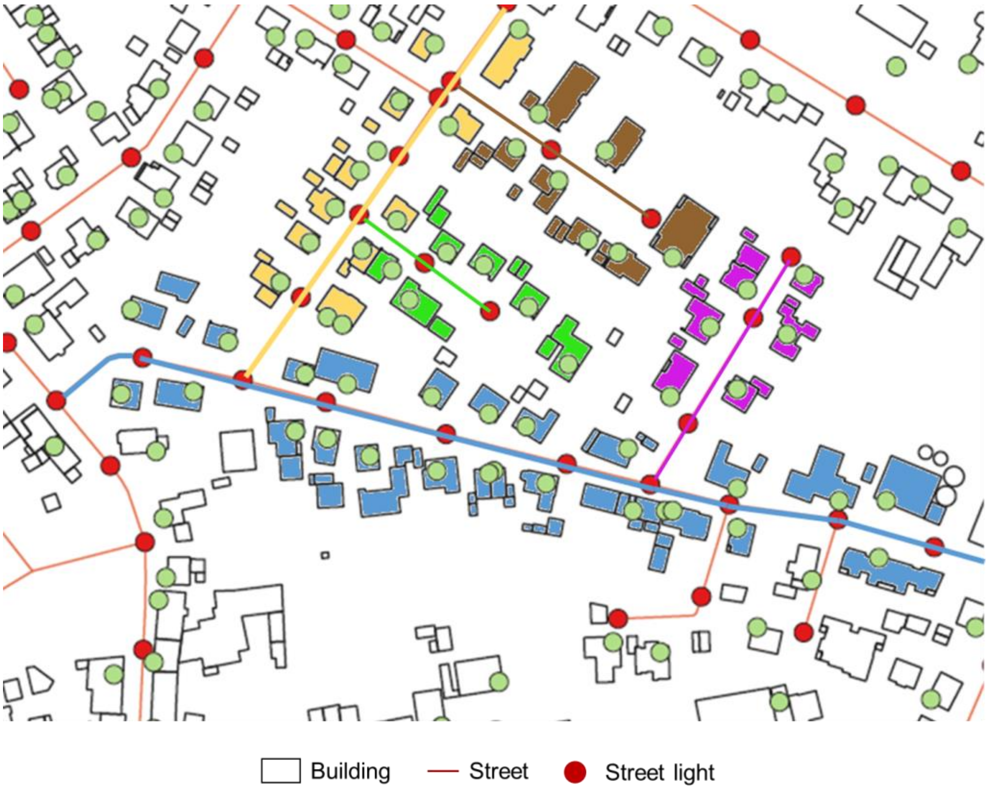

Figure 7 Building street allocation

In reality, the buildings are not all on the same level, nor are they free of obstacles. However, in the absence of terrain data and information on vegetation or other obstacles, an access route had to be determined that offered the highest possible probability of line of sight (see basic assumptions). This seems most likely to apply to access via the building front to the nearest road. Unnecessarily long distances and especially vegetation (e.g. trees in the garden) via the back of the building are thus avoided.

In a next step, all buildings were therefore assigned to a specific street. This is shown as an example in Figure 7. The buildings marked in blue are assigned to the street marked in blue. The buildings marked yellow are assigned to the street marked yellow, and so on.

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Furthermore, this procedure prevents multiple coverage for a single building, which could lead to more network elements and thus to an incomprehensibly higher energy demand.

To now determine the number of AUs, the line of sight from the possible FWA locations to the buildings is checked.

First, the FWA locations at the street intersections are considered. They enable the coverage of buildings on several streets with one location. For this purpose, six sectors of 60° are considered at an intersection location (360° full circle - the 60° sectors are a definition and represent an average value of the systems available on the market). Buildings to which a line of sight exists are marked as supplied. Sectors that do not reach any buildings are discarded.

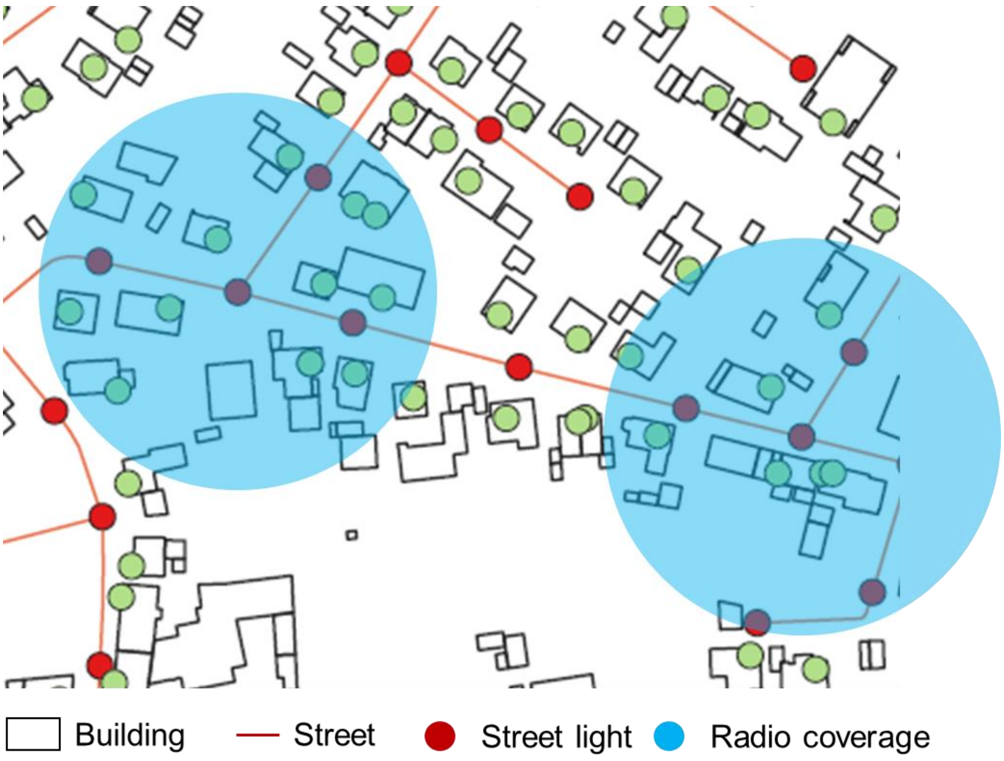

Figure 8: Coverage calculation at road junctions.

In the next step, further FWA locations with four 60° sectors are set up in each street at a defined distance (n x 50 m) and the coverage (line of sight) of the buildings assigned to the street is checked (compare Figure 9). Sectors that do not reach any buildings are discarded.

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This step is repeated until all buildings to be covered with FWA have been reached.

Overall, this model can be used to determine the number of FWA sites and sectors needed in the model region. Each sector represents one FWA Access Unit (active radio unit).

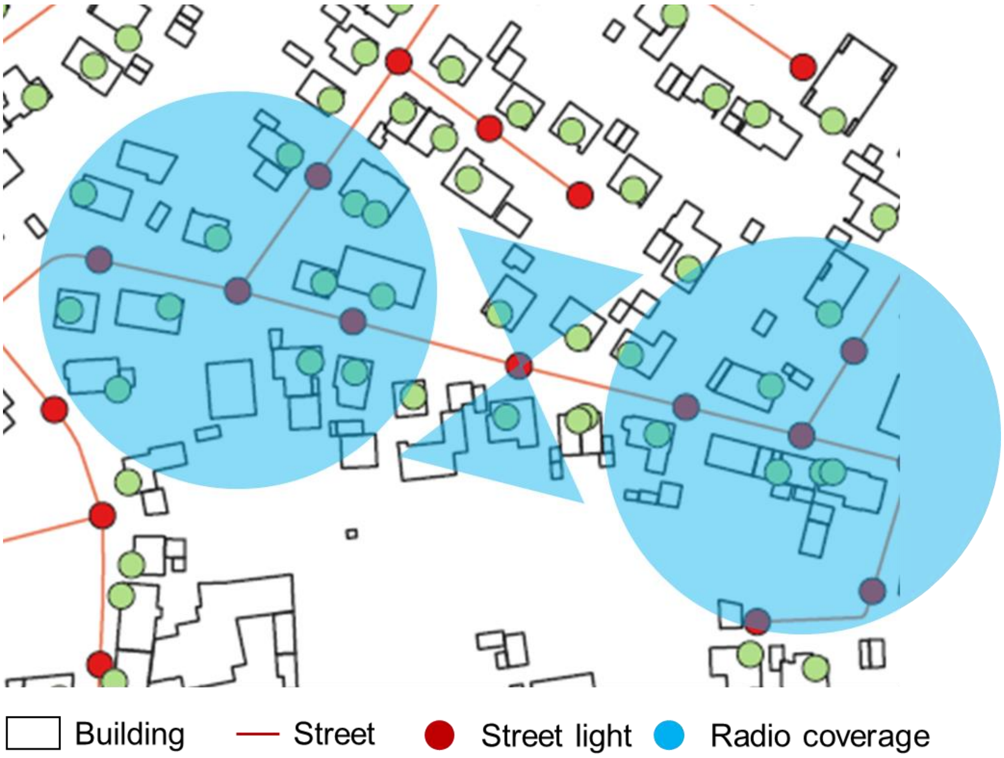

Figure 9: Building coverage between two road intersections.

5.2 To proof line of sight

To check whether there is a line of sight to a building from an FWA location, the respective radio sector (here 60°) is traversed in 0.5° steps and it is checked whether a building can be reached within the defined radio range. If at least ten consecutive checks for a building give a positive result - i.e. the building is reached with at least 5° - a line of sight exists (see Figure 10).

This test is carried out to detect (partial) occlusions, e.g. by other buildings, and to ensure that sufficient building surface is reached so that the receiver unit can be mounted and reached.

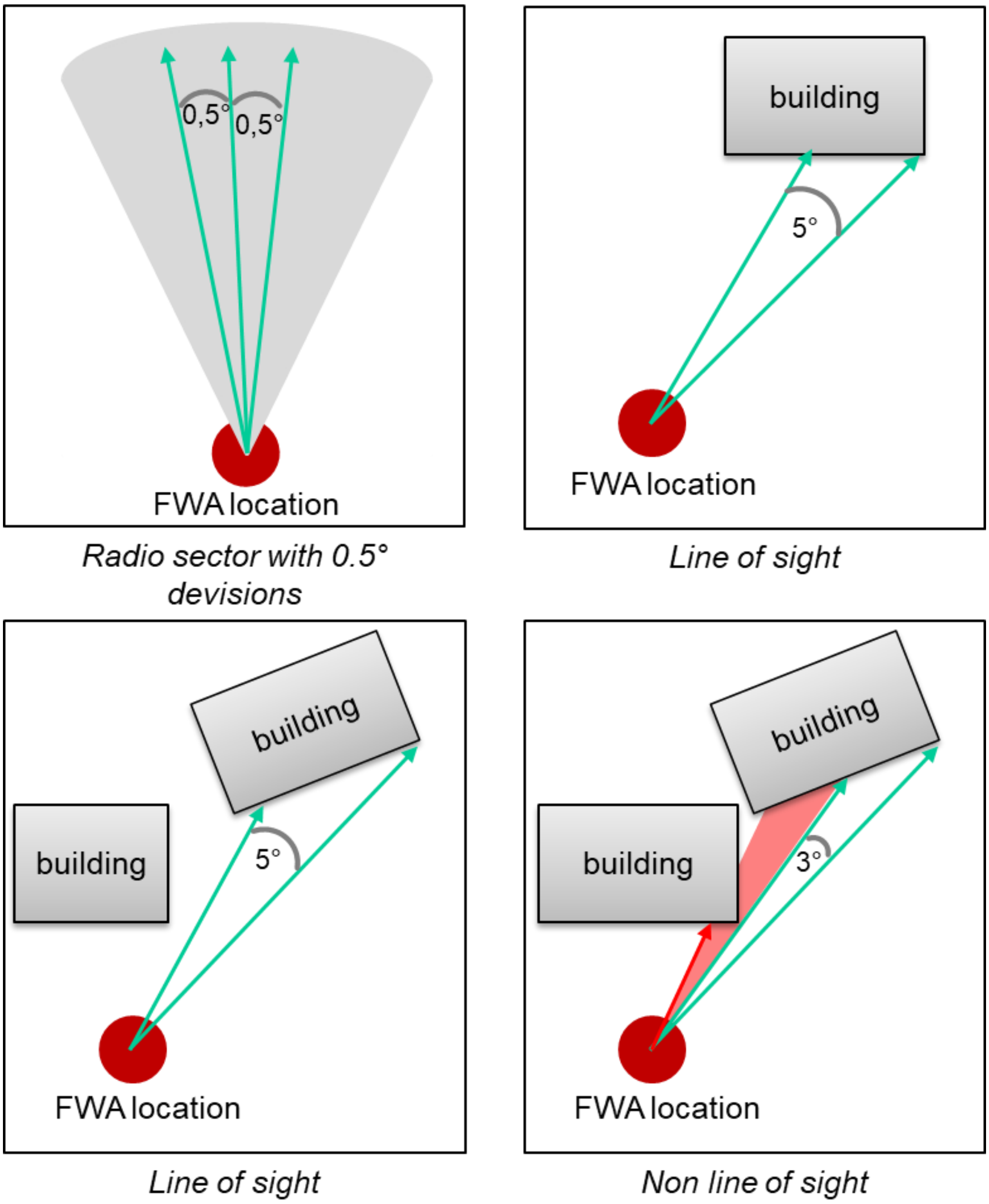

Figure 10: Method for checking whether a line of sight exists.

6 Results

As described at the beginning, fixed wireless access is not a special technology, but rather a topology or structure that can be implemented using various technologies, from WLAN to 5G, and therefore also differs in its respective technical specifics.

An attempt was therefore made to find a general approach that does justice to a large number of these systems, regardless of their technological characteristics.

For example, it has been shown that the technically achievable radio range is generally not important in the settlement environments of the model region. The range is rather limited by the built-up area or other obstacles. In the case of single sites, the radio range can of course play a role, since a higher radio range also allows a greater distance of the single site to the settlement area. However, this accounts for a minority of the connections considered.

This model therefore does not work with technically achievable radio ranges, but with radio ranges in relation to the distance of the FWA locations.

As already described, FWA AUs with 60° radio sectors are considered in this model. This is a determination; as different systems are available on the market - from 30° to over 90°.

Depending on the performance and range of the systems, the power consumption is also very different. Therefore, a corridor is defined in this analysis to allow a realistic estimation. For the FWA-AUs, a minimum power consumption of 5 watts, a maximum power consumption of 15 watts and an average power consumption of 10 watts are assumed.

The same applies to the CPE.

Other technological aspects, such as beamforming, were not taken into account.

6.1 Model 1

In the first model, the radio range was limited to 100 m and the distance between the FWA sites was set to 150 m.

Under these conditions, 23,738 subscribers could be reached. 2,106 possible subscribers could not be reached. These are possible subscribers in individual locations outside the settlement areas.

To reach the 23,738 subscribers of model 1, 2,601 FWA locations with 5,681 FWA AUs are needed.

The table in Figure 11 shows the power consumption, energy consumption and resulting CO2 emissions for a 24-hour, 365-day operation. If an average FWA AU requires about 10 watts (P avg.), the total power consumption of the AUs in the model region is 57 kW, or about 200 tonnes of CO_2 emissions per year.

Access Units

		power consumption per Access Unit			
		P min [W] 5	P avg [W] 10	P max [W] 15	
# FWA Access Units	5.681	28	57	85	power consumption [kW]
Operating hours	24x365	248.828	497.656	746.483	energy consumption per year [kWh]
CO_2 per kWh [g/kWh]	401	99.779.948	199.559.896	299.339.843	CO_2 emission per year [g]
		100	200	299	CO_2 emission per year [to]

Figure 11: Table of power consumption and CO_2 emissions in Model 1.

However, the FWA AUs alone are not sufficient to realise coverage. As described in the definition of the FWA access network, each AU is connected to the point of presence (PoP) and thus to the core network via a fibre optic line.

Due to the spatial location of the FWA AUs, the AUs were merged in 8 PoPs of different sizes (see Figure 12). The PoP size given is not to be understood as a maximum size, but rather as a size category in relation to its energy efficiency.

This allows for some leeway in terms of assigning AUs to the different Pops based on geographical location. This results in a power consumption for all PoPs of approx. 16 kW and an annual CO_2 emission of approx. 57 tonnes (see Figure 13).

The FWA access network thus has a power consumption of almost 74 kW.

PoPs

PoP size	Power consumption (incl. Air conditioning) P/subscriber [W]	Number of PoPs	Number of subscribers	Total Power consumption P [W]
1,000	2.30	2	2,000	4,600
750	2.60	2	1,690	4,394
500	3.20	2	1,326	4,243
250	4.50	2	665	2,993
total		8	5,681	16,230

Figure 12: Assignment of AUs and subscribers to the PoPs as well as the resulting power consumption - model 1.

Operating hours	24x365	142,172	energy consumption per year [kWh]
CO_2 per kWh [g/kWh]	401	57,011,041	CO_2 emission per year [g]
		57	CO_2 emission per year [to]

Figure 13: Energy consumption and CO_2 emissions of the PoPs per year – model 1.

However, in order for a customer to be able to connect to the Internet, he or she still needs an access device (modem, router), in this case FWA customer premises equipment (CPE). This CPE connects to the FWA-AU via radio and provides a cable (RJ45 Ethernet) and/or WLAN interface for the users' end devices. Therefore, each connected subscriber needs a CPE.

As with the FWA-AUs, a power consumption corridor is also assumed for the FWA-CPE. Here, too, the estimated power consumption is between 5 W and 15 W.

An average FWA-CPE has a power consumption of 10 watts (P avg.). With 23,736 connected subscribers and thus 23,736 CPE required, the power consumption is around 237 kW. This corresponds to an annual CO_2 emission of 834 tonnes (see Figure 14).

Customer Premises Equipment

		power consumption per CPE			
		P min [W]	P avg [W]	P max [W]	
		5	10	15	
# FWA CPE	23,736	119	237	356	power consumption [kW]
Operating hours	24x365	1,039,637	2,079,274	3,118,910	energy consumption per year [kWh]
CO_2 per kWh [g/kWh]	401	416,894,357	833,788,714	1,250,683,070	CO_2 emission per year [g]
		417	834	1,251	CO_2 emission per year [to]

Figure 14: Power consumption of the required CPE in the model region – model 1.

In total, the FWA infrastructure requires an average of 310 kW to connect 23,736 subscribers, which corresponds to an annual CO2 emission of approximately 1,000 tonnes (see Figure 15).

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Total Power consumption FWA Access Structure

	P min [W] 5	P avg [W] 10	P max [W] 15	
power consumption PoP	16	16	16	**power consumption [kW]**
power consumption Access Unit	28	57	85	
power consumption Customer Premises Equipment	119	237	356	
Total Power consumption	163	310	457	
	1,430,637	2,719,101	4,007,566	**energy consumption per year [kWh]**
	574	1,090	1,607	**CO_2 emission per year [to]**

Figure 15: Total power consumption of FWA access network and CPE – model 1.

The previous considerations assume that every demanded data rates can be provided to the subscribers with an FWA connection. Of course, this is not true. This is determined by the systems used, e.g. maximum data throughput, technical limitation of subscribers per AU, but also by corporate strategic decisions, such as minimum data rate per subscriber, overbooking, etc.

The table in Figure 16 shows the effects this can have on the necessary infrastructure and thus on energy consumption.

	Subscriber limit / sector	1	2	3	4	5	6	7	8	9	10	15	20	25	30	no limit
	Number of sectors	23,738	13,420	10,151	8,548	7,598	7,042	6,646	6,377	6,174	6,041	5,781	5,722	5,704	5,693	5,681
	additional sectors	18,057	7,739	4,470	2,867	1,917	1,361	965	696	493	360	100	41	23	12	-
power consumption	min [kW]	119	67	51	43	38	35	33	32	31	30	29	29	29	28	28
	max [kW]	356	201	152	128	114	106	100	96	93	91	91	86	86	85	85
energy consumption per year	min [kWh]	1,039,724	587,796	444,614	374,402	332,792	308,440	291,095	279,313	270,421	264,596	253,208	250,624	249,835	249,353	248,828
	max [kWh]	3,119,173	1,763,388	1,333,841	1,123,207	998,377	925,319	873,284	837,938	811,264	793,787	759,623	751,871	749,506	748,060	746,483
CO2 emission per year	min [to]	417	236	178	150	133	124	117	112	108	106	102	101	100	100	100
	max [to]	1,251	707	535	450	400	371	350	336	325	318	305	302	301	300	299

Figure 16: Impact of the subscriber limit per AU on the required FWA infrastructure and energy consumption – model 1.

Examples for the limitation of subscribers per AU:

- If the FWA equipment used allows a maximum number of subscribers of 10 per AU for technical reasons, 360 additional AUs are required due to the distribution of subscribers among the AUs in the model region.

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- If the FWA equipment used allows a maximum throughput of 1 GBit/s at an AU and each subscriber should always have at least 50 Mbit/s available, the number of subscribers per AU is limited to 20. This means 41 additional AUs in the model region.
- If the FWA equipment used allows a maximum throughput of 3 GBit/s at an AU and each subscriber should always have at least 1 GBit/s available, the number of subscribers per AU is limited to 3. This means 4,470 additional AUs in the model region.

Figure 17 also shows this graphically. The smaller the number of subscribers per AU, for whatever reason, the more AUs are needed to connect the given number of subscribers. This of course also increases the energy consumption.

Figure 17 also shows the energy consumption corridor of P min. 5 watts per AU / CPE and P max. 15 watts per AU / CPE.

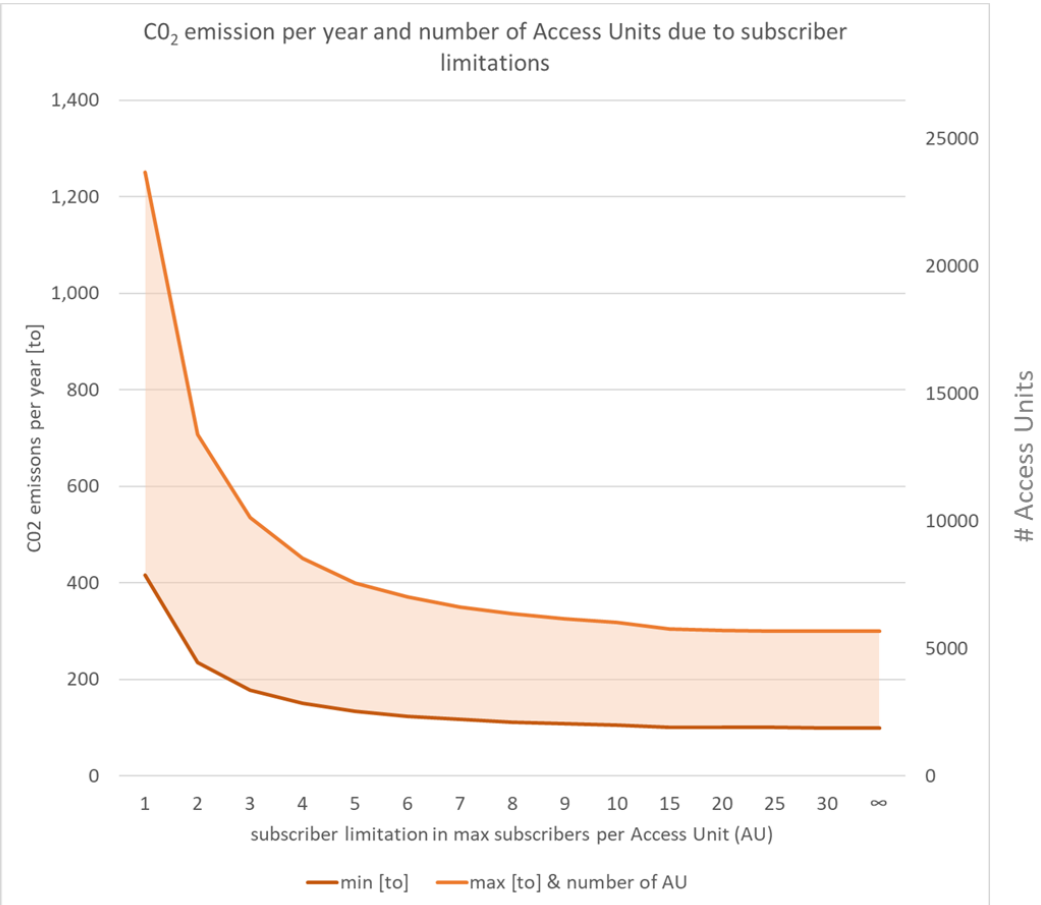

Figure 17: Changes in CO2 emissions and required AUs as a function of the number of subscribers per AU – model 1.

6.2 Model 2

In the second model, the radio range was limited to 200 m and the distance between the FWA sites was set also to 200 m.

Under these conditions, 24,362 subscribers could be reached. 1,482 possible subscribers could not be reached. These are possible subscribers in individual locations outside the settlement areas.

To reach the 24,362 subscribers of model 2, 2,095 FWA locations with 4,598 FWA AUs are needed.

The table in Figure 18 shows the power consumption, energy consumption and resulting CO_2 emissions for a 24-hour, 365-day operation. If an average FWA AU requires about 10 watts (P avg.), the total power consumption of the AUs in the model region is 46 kW, or about 162 tonnes of CO_2 emissions per year.

		Access Units			
		power consumption per Access Unitt			
		P min [W]	P avg [W]	P max [W]	
		5	10	15	
# FWA Access Units	4,598	23	46	69	power consumption [kW]
Operating hours	24x365	201,392	402,785	604,177	energy consumption per year [kWh]
CO_2 per kWh [g/kWh]	401	80,758,352	161,516,705	242,275,057	CO_2 emission per year [g]
		81	162	242	CO_2 emission per year [to]

Figure 18: Table of power consumption and CO_2 emissions in Model 2.

However, the FWA AUs alone are not sufficient to realise coverage. As described in the definition of the FWA access network, each AU is connected to the point of presence (PoP) and thus to the core network via a fibre optic line.

Due to the spatial location of the FWA AUs, the AUs were merged in 8 PoPs of different sizes (see Figure 19). This results in a power consumption for all PoPs of approx. 13.5 kW and an annual CO_2 emission of approx. 47 tonnes (see Figure 20).

The FWA access network thus has a power consumption of almost 60.5 kW.

PoPs

PoP size	Power consumption (incl. Air conditioning) P/subscriber [W]	Number of PoPs	Number of subscribers	Total Power consumption P [W]
1,000	2.30	2	2,000	4,600
500	3.20	5	2,472	7,910
100	7.20	1	126	907
total		8	4,598	13,418

Figure 19: Assignment of AUs and subscribers to the PoPs as well as the resulting power consumption – model 2.

Operating hours	24x365	117,538	energy consumption per year [kWh]
CO_2 per kWh [g/kWh]	401	47,132,809	CO_2 emission per year [g]
		47	CO_2 emission per year [to]

Figure 20: Energy consumption and CO_2 emissions of the PoPs per year – model 2.

However, in order for a customer to be able to connect to the Internet, he or she still needs an access device (modem, router), in this case FWA customer premises equipment (CPE). This CPE connects to the FWA-AU via radio and provides a cable (RJ45 Ethernet) and/or WLAN interface for the users' end devices. Therefore, each connected subscriber needs a CPE.

As with the FWA-AUs, a power consumption corridor is also assumed for the FWA-CPE. Here, too, the estimated power consumption is between 5 W and 15 W.

An average FWA-CPE has a power consumption of 10 watts (P avg.). With 24,361 connected subscribers and thus 24,361 CPE required, the power consumption is around 244 kW. This corresponds to an annual CO_2 emission of 856 tonnes (see Figure 21).

Customer Premises Equipment

		power consumption per Customer Premises Equipment			
		P min [W]	P avg [W]	P max [W]	
		5	10	15	
# FWA CPE	24,361	122	244	365	power consumption [kW]
Operating hours	24x365	1,067,012	2,134,024	3,201,035	energy consumption per year [kWh]
CO_2 per kWh [g/kWh]	401	427,871,732	855,743,464	1,283,615,195	CO_2 emission per year [g]
		428	856	1,284	CO_2 emission per year [to]

Figure 21: Power consumption of the required CPE in the model region – model 2.

In total, the FWA infrastructure requires an average of 303 kW to connect 24,361 subscribers, which corresponds to an annual CO_2 emission of approximately 1,000 tonnes in the P avg. 10 Watt consideration (see Figure 22).

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Total Power consumption FWA Access Structure

	P min [W]	P avg [W]	P max [W]	
	5	10	15	
power consumption PoP	13,5	13,5	13,5	power consumption [kW]
power consumption per Access Unit	23	46	69	
power consumption per CPE	122	244	365	
Total Power consumption	158	303	448	
	1,385,942	2,654,346	3,922,7750	energy consumption per year [kWh]
	555	1,064	1,573	CO_2 emission per year [to]

Figure 22: Total power consumption of FWA access network and CPE – model 2.

The previous considerations assume that every demanded data rate can be provided to the subscribers with an FWA connection. Of course, this is not true. This is determined by the systems used, e.g. maximum data through-put, technical limitation of subscribers per AU, but also by corporate strategic decisions, such as minimum data rate per subscriber, overbooking, etc.

The table in Figure 23 shows the effects this can have on the necessary infra-structure and thus on energy consumption.

	Subscriber limit / sector	1	2	3	4	5	6	7	8	9	10	15	20	25	30	no limit
	Number of sectors	24,362	13,447	9,922	8,194	7,176	6,526	6,106	5,786	5,533	5,359	4,889	4,716	4,651	4,629	4,598
	additional sectors	19,764	8,849	5,324	3,596	2,578	1,928	1,508	1,188	935	761	291	118	53	31	-
power consumption	min [kW]	122	67	50	41	36	33	31	29	28	27	24	24	23	23	23
	max [kW]	365	202	149	123	108	98	92	87	83	80	80	71	70	69	69
energy consumption per year	min [kWh]	1,067,056	588,979	434,584	358,897	314,309	285,839	267,443	253,427	242,345	234,724	214,138	206,561	203,714	202,750	201,392
	max [kWh]	3,201,167	1,766,936	1,303,751	1,076,692	942,926	857,516	802,328	760,280	727,036	704,173	642,415	619,682	611,141	608,251	604,177
CO2 emission per year	min [to]	428	236	174	144	126	115	107	102	97	94	86	83	82	81	81
	max [to]	1,284	709	523	432	378	344	322	305	292	282	258	248	245	244	242

Figure 23: Impact of the subscriber limit per AU on the required FWA infrastructure and energy con-sumption – model 2.

Examples for the limitation of subscribers per AU:

- If the FWA equipment used allows a maximum number of subscribers of 10 per AU for technical reasons, 761 additional AUs are required due to the distribution of subscribers among the AUs in the model region.
- If the FWA equipment used allows a maximum throughput of 1 GBit/s at an AU and each subscriber should always have at least 50 Mbit/s

available, the number of subscribers per AU is limited to 20. This means 118 additional AUs in the model region.

- If the FWA equipment used allows a maximum throughput of 3 GBit/s at an AU and each subscriber should always have at least 1 GBit/s available, the number of subscribers per AU is limited to 3. This means 5,324 additional AUs in the model region.

This is also shown in Figure 24 graphically. The smaller the number of subscribers per AU, for whatever reason, the more AUs are needed to connect the given number of subscribers. This of course also increases the energy consumption.

Figure 24 also shows the energy consumption corridor of P min. 5 watts per AU / CPE and P max. 15 watts per AU / CPE.

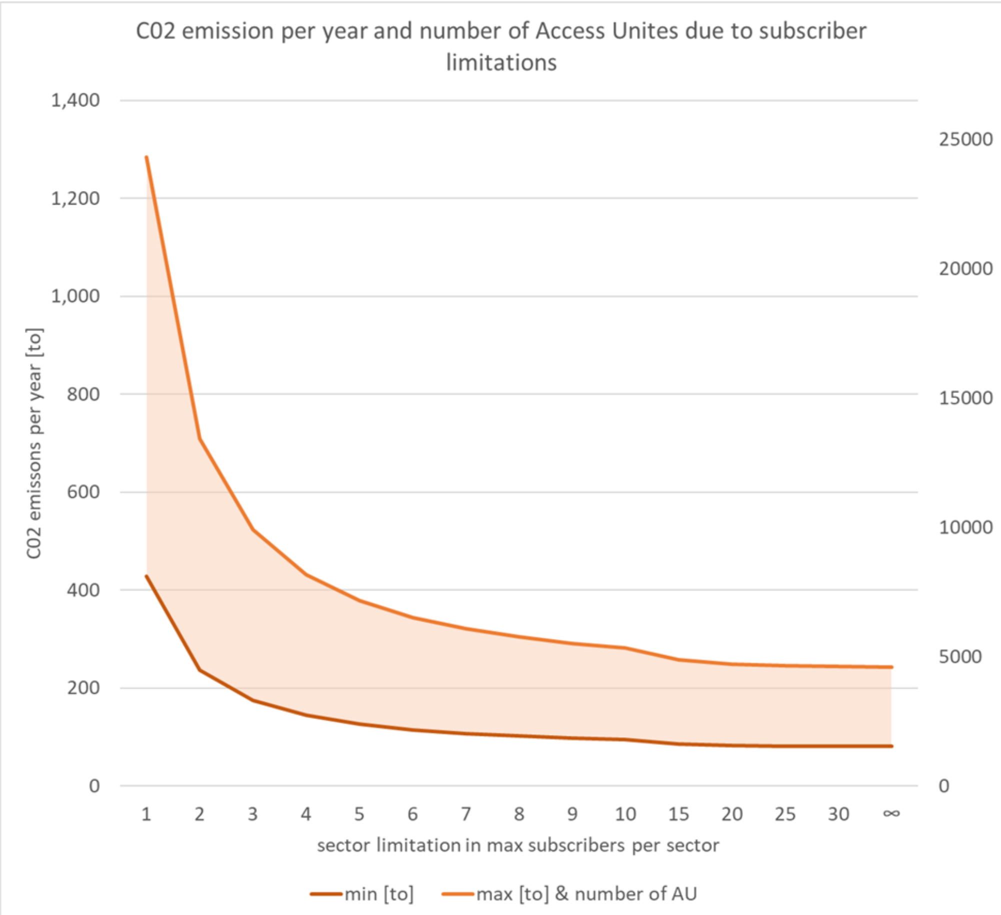

Figure 24: Changes in CO2 emissions and required AUs as a function of the number of participants per AU – model 2.

6.3 Comparison of model 1 and model 2

The two models differ in the assumed radio range and the distance between the FWA sites:

- Model 1: Radio range 100 m, distance between FWA sites 150 m.
- Model 2: Radio range 200 m, distance between FWA sites 200 m.

By doubling the radio range, 624 additional subscribers could be reached in model 2 compared to model 1. The average number of subscribers per AU increased from 4.2 in model 1 to 5.3 in model 2. As a consequence, the number of AUs required in model 2 decreased by 1.083 compared to model 1.

If we now compare the power consumption, we see that the total power consumption differs by 7 kW from model 1 to model 2 (see Figure 25). This is above the expected value of 4.6 kW in favour of model 2. The additional reduction results from the spatial distribution of the AUs which have to be connected to the PoPs. This is more advantageous in model 2, so that although the same amount, somewhat larger and thus more efficient PoPs are required.

Overall, however, the difference is quite small.

Total Power consumption FWA Access Structure

	Model 1 P avg [W]	Model 2 P avg [W]	
power consumption PoP	16	13,5	power consumption [kW]
power consumption per Access Unit	57	46	
power consumption per CPE	237	244	
Total Power consumption	310	303	
	2,719,101	2,654,346	energy consumption per year [kWh]
	1,090	1,064	CO_2 emission per year [to]

Figure 25: Comparison of power consumption and CO_2 emissions of models 1 and 2.

Overall, it can be seen that the energy consumption in the access network depends less on the absolute number of subscribers or radio range than on the number of subscribers per AU (see Figure 26 and Figure 27). The energy consumption of the CPE naturally scales linearly with the number of subscribers.

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	Subscriber limit / sector	1	2	3	4	5	6	7	8	9	10	15	20	25	30	no limit
	Number of sectors	23,738	13,420	10,151	8,548	7,598	7,042	6,646	6,377	6,174	6,041	5,781	5,722	5,704	5,693	5,681
	additional sectors	18,057	7,739	4,470	2,867	1,917	1,361	965	696	493	360	100	41	23	12	-
power consumption	min [kW]	119	67	51	43	38	35	33	32	31	30	29	29	29	28	28
	max [kW]	356	201	152	128	114	106	100	96	93	91	91	86	86	85	85
energy consumption per year	min [kWh]	1,039,724	587,796	444,614	374,402	332,792	308,440	291,095	279,313	270,421	264,596	253,208	250,624	249,835	249,353	248,828
	max [kWh]	3,119,173	1,763,388	1,333,841	1,123,207	998,377	925,319	873,284	837,938	811,264	793,787	759,623	751,871	749,506	748,060	746,483
CO2 emission per year	min [to]	417	236	178	150	133	124	117	112	108	106	102	101	100	100	100
	max [to]	1,251	707	535	450	400	371	350	336	325	318	305	302	301	300	299

Figure 26: Model 1 – power consumption of AU due to max subscribers per AU.

	Subscriber limit / sector	1	2	3	4	5	6	7	8	9	10	15	20	25	30	no limit
	Number of sectors	24,362	13,447	9,922	8,194	7,176	6,526	6,106	5,786	5,533	5,359	4,889	4,716	4,651	4,629	4,598
	additional sectors	19,764	8,849	5,324	3,596	2,578	1,928	1,508	1,188	935	761	291	118	53	31	-
power consumption	min [kW]	122	67	50	41	36	33	31	29	28	27	24	24	23	23	23
	max [kW]	365	202	149	123	108	98	92	87	83	80	80	71	70	69	69
energy consumption per year	min [kWh]	1,067,056	588,979	434,584	358,897	314,309	285,839	267,443	253,427	242,345	234,724	214,138	206,561	203,714	202,750	201,392
	max [kWh]	3,201,167	1,766,936	1,303,751	1,076,692	942,926	857,516	802,328	760,280	727,036	704,173	642,415	619,682	611,141	608,251	604,177
CO2 emission per year	min [to]	428	236	174	144	126	115	107	102	97	94	86	83	82	81	81
	max [to]	1,284	709	523	432	378	344	322	305	292	282	258	248	245	244	242

Figure 27: Model 2 – power consumption of AU due to max subscribers per AU.

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7 Radio propagation simulation

The model presented in the previous chapters is based on a structural approach, which is particularly based on the relative spatial location of FWA sites to the buildings to be covered. Only a few technical parameters were taken as a basis here:

- Radio frequency: 60 Ghz
- Connection type: line of sight
- Data throughput per AU
- Minimum data rate per user or maximum number of users per AU

From this, the number of required FWA sites and AUs could be determined. The radio range only played a minor role in this model, as it only influences the reachability of remote individual buildings. For the majority of potential subscribers, it is insignificant.

In order to verify this structural model and to take into account other influencing variables such as non-line of sight connections (NLOS) and the frequency range of 26 GHz, which is more advantageous in terms of propagation, a check of the radio propagation conditions was carried out for each building on the basis of the locations determined in the previous model analysis. These reviews are based on the technical specifications of the Radio Access Network Group of the 3GPP[1] and the papers *Was bringt die 5. Genration Mobilfunk (5G)? – Herausforderungen und Potenziale* [2] and *5G Fixed-Wireless-Access simulation using real building data for rural areas*[3].

In the following, the models and equations used are briefly explained. Subsequently, an overview of the results is given.

[1] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on channel model for frequencies from 0.5 to 100 GHz (Release 16)
[2] Script: Was bringt die 5. Genration Mobilfunk (5G)? – Herausforderungen und Potenziale; Prof. Dr. Lüders
[3] 5G Fixed-Wireless-Access simulation using real building data for rural areas; Stephan Sauerwald

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7.1 Models and equations used

The aim was to determine the radio propagation conditions, in particular the receiving level and data rate, on the basis of the 3GPP models. The building attenuation was also included in the model.

It should be noted at this point that the 3GPP uses different designations than in the previous considerations:

- FWA Access Unit (AU) ≙ Base Station (BS)
- Customer Premises Equipment (CPE) ≙ User Terminal (UT)

In the following, the designations of the 3GPP are used in the formulae in order to remain comprehensible and consistent with regard to the sources. In the explanations, the previous designations are used to ensure a link to the previous considerations.

The reception level is calculated according to the following formula:

$$RXLEV = bstxpwr - bslcab + bsgant - PL - L_{building} + utgant - utlcab$$

- RXLEV: receiving level user terminal
- bstxpwr: transceive level base station = 30 dBm
- bslcab: cable attenuation base station = 2 dB
- bsgant: antenna gain base station = 20 dBi
- PL: Pathloss
- $L_{building}$: building attenuation
- utgant: antenna gain user terminal = 0 dB
- utlcab: cable attenuation user terminal = 0 dB

For the AU, a transmission power of bstxpwr = 30 dBm is assumed, as well as a cable attenuation bslcab = 2 dB and an antenna gain bsgant = 20 dBi.

Since it can be assumed that the customer premises equipment will usually be designed as a single unit without a remote directional antenna, neither cable attenuation utlcab = 0 dB nor antenna gain utgant = 0 dB are assumed.

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The calculation of the path loss PL and the building attenuation $L_{building}$ is described in more detail below.

Various models are available for calculating the path loss between base station and receiver. In this analysis, the propagation model for 4G and 5G of the 3GPP[4] is used. This is an empirical model which provides adapted formulas for different scenarios.

In particular, the model distinguishes between line of sight (LOS) - free line of sight between AU and CPE - and non line of sight (NLOS) - no free line of sight between AU and CPE.

Line of sight connections are again differentiated by the so-called breakpoint distance. The breakpoint distance dBP can be calculated with the following formula:

$$d_{BP} = 4 \cdot h'_{BS} \cdot h'_{UT} \cdot f[Hz] \cdot c$$

- h_{BS} : Basestation hight= 5 meter
- h_{UT} : User Terminal hight = 1,5 meter
- h'_{BS} : h_{BS} – 1 meter
- h'_{UT} : h_{UT} – 1 meter

If the distance d between AU and receiver is smaller than the breakpoint distance d < d_{BP} , the following formula to calculate the path loss is used:

$$PL_1[dB] = 32{,}4 + 21\log_{10} d + 20\log_{10} f[GHz]$$

- d = Distance between BS and UT in meter
- f = Carrier frequency

However, if the distance d between AU and receiver is greater than the breakpoint distance d > d_{BP}, the path loss is calculated as follows:

$$PL_2[dB] = 32{,}4 + 21\log_{10} d + 20\log_{10} f[GHz] - 9{,}5\log_{10}(d_{BP}^2 + (h_{BS} - h_{UT})^2)$$

[4] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on channel model for frequencies from 0.5 to 100 GHz (Release 16), Page 27

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The calculation of the path loss at d > d_{BP} depends on the carrier frequency as well as on the height difference between AU and CPE.

If there is no line of sight (NLOS) between AU and CPE, the path loss is calculated as follows:

$$PL_{NLOS}[dB] = 35{,}3 + 21\log_{10} d + 22{,}4 + 21{,}3\log_{10} f - 0{,}3 \cdot (h_{UT} - 1{,}5)$$

As already mentioned at the beginning, the building attenuation is also included in the calculations. This describes the loss that occurs during the penetration of building walls and windows. Here, too, a model from the 3GPP[5] was used.

This model assumes that the walls to be penetrated are mainly concrete and double-glazed, non-metal coated windows.

The attenuations for the concrete wall and window components are calculated as follows:

$$L_{glas}[dB] = 2 + 0{,}2f$$

$$L_{concrete}[dB] = 5 + 4f$$

Since the exact construction type of the buildings is unknown and varies, a standard attenuation for the buildings was calculated:

$$L_{building}[dB] = 5 - 10\log_{10}\left(0{,}3 \cdot 10^{\frac{-L_{glas}}{10}} + 0{,}7 \cdot 10^{\frac{-L_{concrete}}{10}}\right)$$

- Carrier frequency f = 26 GHz
- Building attenuation $L_{building}$ = 17,4 dB

Previous considerations of building attenuation do not currently take into account the angle of impact of the radio waves on the building. However, since impact angles deviate from 90° to the wall, further losses occur that must be taken into account.

[5] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on channel model for frequencies from 0.5 to 100 GHz (Release 16), Page 31

The losses caused by the angle of impact can be calculated by the following formula:

$$L_{angle}[dB] = 10 \cdot (1 - \cos \alpha)^2 + 10 \cdot (1 - \cos \beta)^2$$

The angle α is the angle in the horizontal and β is the angle in the vertical (see Figure 28)

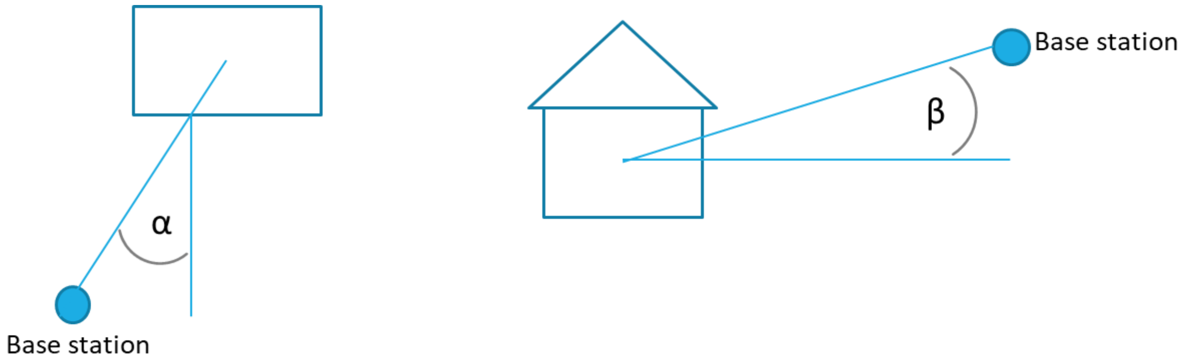

Figure 28: Representation of the angles of impact angle α and β.

Using the formulas shown, the receiving levels can now be calculated for each building. It should be noted at this point that no distinction was made here between multi- or single-occupancy buildings. A single receiving level was calculated for each building, whereby the CPE is always positioned on the ground floor and on the accessible side of the building. Other negative influences such as vegetation or weather were also not taken into account. This is therefore a best-case consideration.

Using the calculated receiving level, the signal to noise ratio (SNR) can now be determined. The signal power corresponds to the calculated receiving level. The noise power at the receiver is determined by the following formula.

Noise power at the user terminal in mW:

$$n_{UT} = z_{UT} \cdot kT[mWs] \cdot B[Hz]$$

Noise level at the user terminal in dBm:

$$N_{UT} = 10 \log_{10}(n_{UT})$$

- $kT = 1{,}38 \cdot 10^{-23} \frac{J}{K} \cdot 290{,}15\,°; K = 4 \cdot 10^{-18} mWs$
- $z_{UT} = 10^{\frac{6\,dB}{10}}$

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The achievable data rate can be calculated via the SNR. A modified Shannon formula is used for this[6].

$$DRate = B_{eff} \cdot \log_2\left(1 + \frac{1}{m} \cdot snr\right)$$

- $B_{eff} = 0{,}8 \cdot B$ mit $B = 400MHz$
- $snr = 10^{\frac{SNR}{10}}$ mit $SNR = RXLEV - Noise\ level$
- $m = implementation\ margin\ (linear) = 10^{\frac{3\,dB}{10}}$

However, the data rate cannot be increased at will, but is limited in particular by the modulation and coding used. This is taken into account by the factor K:

$$D = \min\left(DRate, K \cdot B_{eff}\right)$$

With K = 9 and B_{eff} = 320 Hz, this results in a maximum data rate of D = 2,88 GBit/s.

7.2 Simulation results

Based on the radio propagation model presented briefly, a radio propagation simulation is now carried out on the georeferenced data of the model region.

For this purpose, the already determined FWA locations from the structural model with 150 metre and 200 metre location distances (cf. chapter 6) are used. From each of these locations, the accessibility of the buildings is calculated by means of a LOS or NLOS connection. Buildings that can be reached from an FWA location are removed from the list of uncovered buildings. This eliminates the possibility of multiple coverage in planning.

Due to the fact that each building is only supplied from one FWA location and due to the use of LOS and NLOS connections as well as the radio-technically more advantageous propagation conditions of the lower frequency range of 26 GHz, a partially different allocation of the buildings to the FWA locations

[6] Was bringt die 5. Genration Mobilfunk (5G)? – Herausforderungen und Potenziale; Prof. Dr. Lüders

takes place. As a result, the number of FWA locations is also lower by 34 locations (1.3%) at 150 metre location spacing and 21 locations (1.0%) at 200 metre location spacing.

The following tables show the main results of the simulation:

- Proportion of LOS and NLOS connections
- the average calculated data rate
- the average reception level
- Proportion of connections with a data rate of at least 1 GBit/s

City A

Distance between FWA locations	150 meters	200 meters
Line of sight connections	90%	86%
Non line of sight connections	10%	14%
average calculated data rate	1,40 Gbit/s	1,20 Gbit/s
Avg. Receiving level	-67,0 dB	-69,4 dB
Connections with at least 1 Gbit / s	72.0%	59.5%

Figure 29: Simulation results city A.

City B

Distance between FWA locations	150 meters	200 meters
Line of Sight connections	94%	91%
Non line of sight connections	6%	9%
average calculated data rate	1,33 Gbit/s	1,11 Gbit/s
Avg. Receiving level	-67,8 dB	-70,3 dB
Connections with at least 1 Gbit / s	67.6%	52.8%

Figure 30: Simulation results city B.

City C

Distance between FWA locations	150 meters	200 meters
Line of Sight connections	92%	87%
Non line of sight connections	8%	13%
average calculated data rate	1,41 Gbit/s	1,19 Gbit/s
Avg. Receiving level	-66,7 dB	-69,5 dB
Connections with at least 1 Gbit / s	72.9%	58.4%

Figure 31: Simulation results city C.

City D

Distance between FWA locations	150 meters	200 meters
Line of Sight connections	89%	87%
Non line of sight connections	11%	13%
average calculated data rate	1,37 Gbit/s	1,22 Gbit/s
Avg. Receiving level	-67,6 dB	-69,4 dB
Connections with at least 1 Gbit / s	69.2%	59.9%

Figure 32: Simulation results city D.

City E

Distance between FWA locations	150 meters	200 meters
Line of Sight connections	89%	85%
Non line of sight connections	11%	15%
average calculated data rate	1,37 Gbit/s	1,21 Gbit/s
Avg. Receiving level	-67,6 dB	-69,6 dB
Connections with at least 1 Gbit / s	69.7%	59.2%

Figure 33: Simulation results city E.

City F

Distance between FWA locations	150 meters	200 meters
Line of Sight connections	94%	91%
Non line of sight connections	6%	9%
average calculated data rate	1,35 Gbit/s	1,15 Gbit/s
Avg. Receiving level	-67,8 dB	-70,2 dB
Connections with at least 1 Gbit / s	68.7%	55.2%

Figure 34: Simulation results city F.

First of all, the tables show that the majority of the buildings can be reached by LOS connections from the selected locations. The share of NLOS connections ranges between 6% and 15%, depending on the city and the distance between locations. It is interesting that the share of connections with a data rate of at least 1 GBit/s does not correspond to the shares of LOS/NLOS connections. The at least 1 GBit/s share is always significantly lower than the LOS share in all cities and is therefore not only dependent on one LOS or NLOS connection.

If one were to demand a minimum data rate of 1 GBit/s[7], it would immediately become clear that the radio connection would have to be improved for many buildings. In addition, in the simulation, the radio connection (receiving level) was always considered on a case-by-case basis. In addition, the connection of several subscribers through one location has not yet been taken into account here.[8] If both the radio propagation and the connection of several subscribers are taken into account, a data rate of 1 GBit/s per subscriber can only be realised through additional locations and equipment.

It becomes clear that even with a more advantageous frequency range - 26 GHz instead of 60 GHz - and with the inclusion of NLOS connections, no significant improvement in coverage or reduction in technical effort can be expected. On the contrary, it becomes clear that for a demand of 1 Gbit/s per subscriber, a location distance of 150 metres still seems to be too large.

Furthermore, this simulation shows that the structural model seems to give a very good impression of the demand for locations and equipment and supports the results of the structural model.

In the following chapter, a comparison of the energy demand of FWA and other infrastructures is now carried out.

[7] See the objectives of the Digital Single Market of the EU Commission
[8] Compare the limitation of the number of subscribers per AU of the structural model of the previous chapter.

8 Energy efficiency of FWA

How energy-efficient is fixed wireless access?

Of course, this question cannot be answered in a general way. Not least because FWA is not a technology, but a topology or structure. The exact implementation, the components used and the usage scenario play a decisive role.

A comparison of the structures of typical access networks in Europe:

- DSL
- HFC
- FTTH PtP
- FTTH GPON

shows that FWA and GPON are both point-to-multipoint systems that have a splitter element close to the subscribers (see Figure 28). Both use a single fibre optic link to connect multiple subscribers. GPON uses a passive optical splitter that splits the fibre optic link between the different subscribers. In contrast, FWA requires additional active radio technology to connect several subscribers to the fibre optic link. However, the number of subscribers that can be connected via an AU is typically smaller than the number of subscribers behind a GPON splitter.

GPON therefore appears to be a suitable comparative structure.

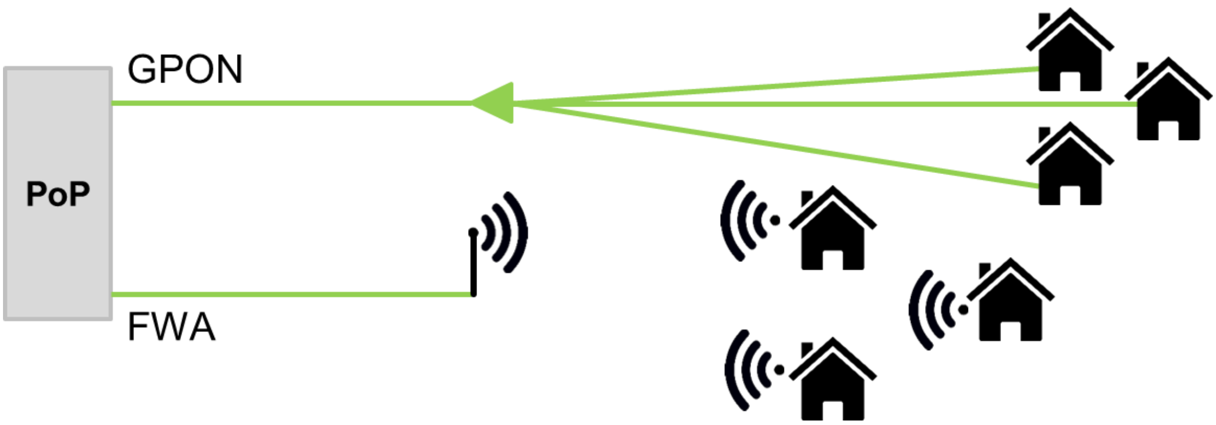

Figure 35: Comparison of GPON and FWA structures.

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The usage scenarios describe the minimum data rate available to each user (exclusively) or the maximum data rate offered. Both are connected via the overbooking factor. These factors are determined by the network operator on the basis of economic considerations.

The technical equipment used (FWA AU and CPE) determines, among other things, the achievable data rates (throughput) or the number of manageable subscribers and, in particular, the energy consumption.

In the following, example scenarios are created that take these points into account and are compared with the results of the main study on GPON.

8.1 Szenario 1 - 3

In scenarios 1 to 3, an FWA AU is used that operates in the frequency range of 57 - 64 GHz, enables a data throughput of 1.8 GBit/s and has a power consumption of 15 watts.

First, at least 50 Mbit/s should be made available to each subscriber. This leads to a limitation of 36 subscribers per AU with the given data throughput. In the previously considered models 1 & 2, this means that there is no subscriber limitation.

	FTTH GPON	FWA Model 1 (P 15W/AU)	FWA Model 2 (P 15W/AU)
Active network elements in the access network	36 PoPs	5,681 AUs & 8 PoPs	4,598 AUs & 8 PoPs
power consumption access network [kW]	19	101,4	82,4
Number of subscribers	25,311	23,738	24,362
Power consumption per subscriber [W]	0.75	4.3	3.4

Figure 36: Comparison GPON / FWA, scenarios 1 - 3, 50 MBit/s.

For the FWA access network (without CPE), this means a power consumption of about 100 kW in model 1 and about 82 kW in model 2. The main study shows a power consumption of 19 kW for GPON. However, since different numbers of subscribers are reached, the power consumption is normalised to one subscriber. This shows that the normalised power consumption per subscriber of GPON is 0.75 W, for FWA 4.3 W in model 1 and 3.4 W in model 2 (see Figure 36).

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In the next step, the minimum data rate is increased to 250 Mbit/s per subscriber. This leads to a limitation of 7 subscribers per AU.

	FTTH GPON	FWA Model 1 (P 15W/AU)	FWA Model 2 (P 15W/AU)
Active network elements in the access network	36 PoPs	5,681 + 965 AUs & 8 + 1 PoPs	4,598 + 1,508 AUs & 8 + 3 PoPs
power consumption access network [kW]	19	101.4 + 18.6	82.4 + 26.5
Number of subscribers	25,311	23,738	24,362
Power consumption per subscriber [W]	0.75	4.3 + 0.75	3.4 + 1.07

Figure 37: Comparison GPON / FWA, scenarios 1 - 3, 250 MBit/s.

This already significantly increases the number of AUs required. In model 1 965 and in model 2 even 1,508 additional AUs are needed. Further PoPs are also required in both models. Accordingly, the power consumption also increases significantly (Figure 37).

In the third step, the minimum data rate per subscriber is increased again, to 500 Mbit/s, which leads to a limit of 3 subscribers per AU.

	FTTH GPON	FWA Model 1 (P 15W/AU)	FWA Model 2 (P 15W/AU)
Active network elements in the access network	36 PoPs	5,681 + 4,470 AUs & 8 + 5 PoPs	4,598 + 5,324 AUs & 8 + 6 PoPs
power consumption access network [kW]	19	101.4 + 77.5	82.4 + 92.81
Number of subscribers	25,311	23,738	24,362
Power consumption per subscriber [W]	0.75	4.3 + 3.2	3.4 + 3.8

Figure 38: Comparison GPON / FWA, scenarios 1 - 3, 500 MBit/s.

A minimum data rate of 500 Mbit/s per subscriber leads to a considerable increase in the number of AUs. In model 1, 4,470 additional AUs are needed, which corresponds to an increase of about 78%. In model 2, the number of AUs must even be more than doubled. Also additional PoPs are needed, 5 in model 1 and 6 in model 2. The power consumption also increases accordingly (Figure 38).

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8.2 Szenario 4 - 6

In scenarios 4 to 6, an FWA AU is used that operates in the frequency range of 57 - 64 GHz, enables a data throughput of 1 GBit/s and has a power consumption of 10 watts.

First, at least 50 Mbit/s should be made available to each subscriber. This leads to a limitation of 20 subscribers per AU with the given data throughput.

	FTTH GPON	FWA Model 1 (P 10W/AU)	FWA Model 2 (P 10W/AU)
Active network elements in the access network	36 PoPs	5,681 + 41 AUs & 8 PoPs	4,598 + 118 AUs & 8 PoPs
power consumption access network [kW]	19	73.54	60.85
Number of subscribers	25,311	23,738	24,362
Power consumption per subscriber [W]	0.75	3.1	2.5

Figure 39: Comparison GPON / FWA, scenarios 4 - 6, 50 MBit/s.

This already means additional AUs in models 1 and 2. Even if this is still quite low with 41 or 118 additional AUs and does not make any additional PoPs necessary (see Figure 39). The normalized power consumption is 3.1 W in model 1 and 2.5 W in model 2.

In the next step, the minimum data rate is increased to 250 Mbit/s per subscriber. This leads to a limitation of 4 subscribers per AU.

	FTTH GPON	FWA Model 1 (P 10W/AU)	FWA Model 2 (P 10W/AU)
Active network elements in the access network	36 PoPs	5,681 + 2,867 AUs & 8 + 3 PoPs	4,598 + 3,596 AUs & 8 + 4 PoPs
power consumption access network [kW]	19	73.54 + 35.02	60.85 + 43.31
Number of subscribers	25,311	23,738	24,362
Power consumption per subscriber [W]	0.75	3.1 + 1.5	2.5 + 1.8

Figure 40: Comparison GPON / FWA, scenarios 4 - 6, 250 MBit/s.

This already significantly increases the number of AUs required. In model 1 by 2,867 and in model 2 by 3,596 additional AUs. Further PoPs are also required in both models. Accordingly, the power consumption also increases significantly (see Figure 40).

In the third step, the minimum data rate per subscriber is increased again, to 500 Mbit/s, which leads to a limit of 2 subscribers per AU.

	FTTH GPON	FWA Model 1 (P 10W/AU)	FWA Model 2 (P 10W/AU)
Active network elements in the access network	36 PoPs	5,681 + 7,739 AUs & 8 + 8 PoPs	4,598 + 8,849 AUs & 8 + 9 PoPs
power consumption access network [kW]	19	73.54 + 94.91	60.85 + 105.06
Number of subscribers	25,311	23,738	24,362
Power consumption per subscriber [W]	0.75	3.1 + 4	2.5 + 4.3

Figure 41: Comparison GPON / FWA, scenarios 4 - 6, 500 MBit/s.

A minimum data rate of 500 Mbit/s per subscriber leads to a considerable increase in the number of AUs. In both models the number of AUs more than doubles. This applies also to the number of PoPs. The power consumption also doubles accordingly (see Figure 41).

8.3 Conclusion from scenarios 1 to 6

In the previous chapters, 6 scenarios were presented. In scenarios 1 to 3, AUs with a data throughput of 1.8 GBit/s and a power consumption of 15 W were used. In scenarios 4 to 6, AUs with a data throughput of 1 GBit/s and a power consumption of 10 W were used.

As has been shown, the minimum data rate per subscriber in particular defines the number of AUs and PoPs required. If the minimum data rate per subscriber increases, the number of necessary AUs also increases. Thus, the energy requirement is also dependent on the minimum data rate per user (*Figure 42*).

			P 15W/AU	P 10W/AU	
Minimum data rate per subscriber	50 MBit/s	Model 1	101.4	73.5	Total power consumption Access Network [kW]
		Model 2	82.3	60.8	
	250 MBit/s	Model 1	118.1	108.5	
		Model 2	108.9	104.1	
	500 MBit/s	Model 1	179.1	168.4	
		Model 2	175.2	165.9	

Figure 42: Overview of the power consumption of scenarios 1 to 6.

9 Summary

This work examines the energy consumption of fixed wireless access infrastructures on the basis of an FWA roll-out in a real model region. This model region consists of 6 municipalities with approximately 56,700 inhabitants and almost 26,000 possible subscribers.

The energy consumption was estimated by determining the active components required of a FWA network. For this purpose, a spatial analysis of the location of the buildings (subscribers) to possible FWA sites along the roads in the model region was made, resulting in the respective number of active components.

The geo-referenced analysis has shown that the technical radio range within the settlement areas plays a subordinate role. Rather, it is limited by buildings and other obstacles. In remote locations outside the settlement areas, the radio range is certainly important. With a high radio range, more individual locations can be reached from the settlement areas. However, it must be taken into account that there is always a trade off between radio range and usable data rate. Here, too, there is a limit to the radio range depending on the data rate the subscriber is aiming for.

Model 2 has shown that by increasing the radio range and the distance between the sites, the number of FWA AUs can be reduced and the number of subscribers reached can be increased. However, these figures quickly become relative as soon as the required data rate per subscriber increases. This makes additional AUs and possibly PoPs necessary in both models. In addition, the energy consumption of both models converges more and more as the required data rate per subscriber is increased. This is to be expected, however, as the number of AUs tends towards the number of subscribers due to the limited data throughput of an AU.

This case, where each subscriber is connected with its own AU, should be avoided as far as possible.

If the system behaviour of FWA is compared to other technologies in terms of the required data rate and necessary active network elements, it quickly becomes apparent that DSL and FWA are almost identical. Compare Figure 17, Figure 24, Figure 43 and Figure 44.

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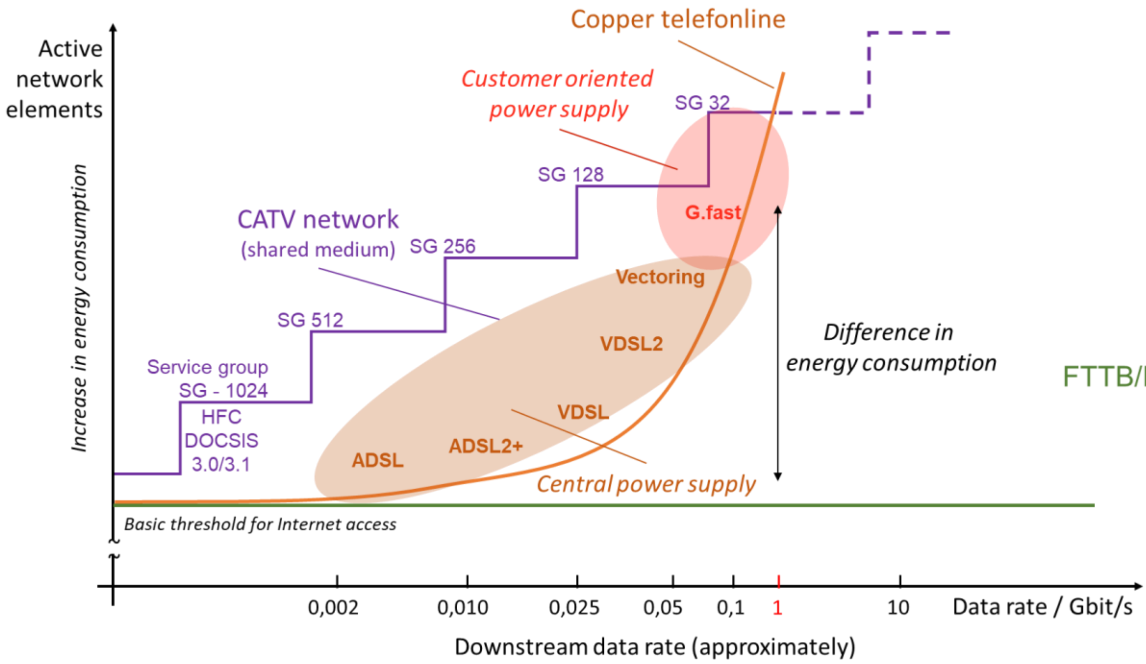

Figure 43: Number of active network elements based on the achievable data rate for DSL, CATV, FTTB/H.

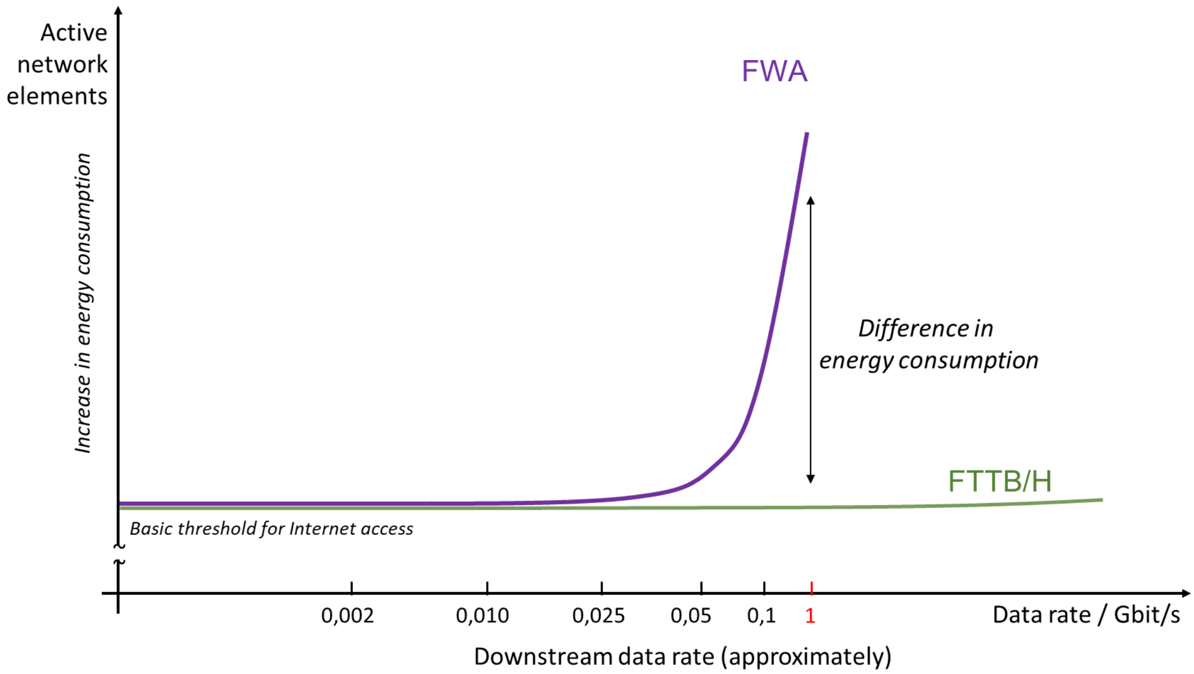

Figure 44: Number of active network elements based on the achievable data rate for FWA and FTTB/H.

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Special attention should be paid to the fact that the energy consumption of the CPE was always greater than that of the FWA access network in all the models and scenarios presented. In both models with P avg. 10 W, the power consumption was around 240 kW, which is 3 to 4 times higher than the access network (see Figure 45).

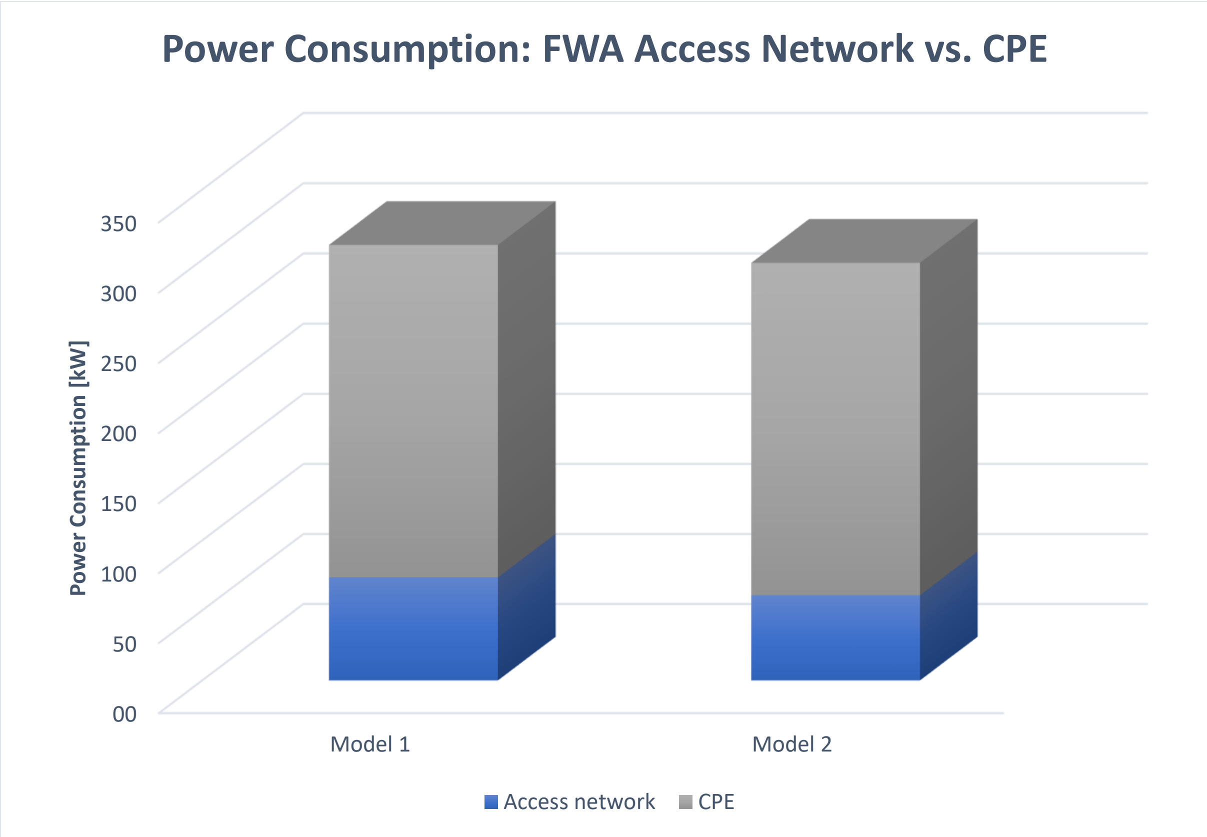

Figure 45: Comparison of energy consumption of FWA Access network and CPE - 50 MBit/s; P avg. 10 W.

Special attention should therefore be paid to improving the energy efficiency of the CPE. Reducing the energy consumption of each CPE by a few watts would have an immensely positive impact on the energy balance. This also applies to other access technologies (DSL, CATV, FTTB/H, etc.), since a CPE is always required.

In addition to developing technically energy-efficient CPE, much can also be achieved organisationally. For example, all CPE could be delivered in a low-power mode as standard and all other technical functions could have to be actively selected by the users via *Opt-In* in order to reduce energy consumption. A *"night setback"* as a standard setting, which shuts down the CPE at night and starts it up again in the morning, also offers considerable potential for savings - especially if this also leads to elements on the network side being put into sleep or low power mode.

The customer premises equipment is a considerable energy sink in relation to the access network, which can and must be designed to be significantly more energy efficient.