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Techno-Economic Analysis for Various Incremental Deployments of Future 6G-based Mobile Networks

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Abstract
Deployment solutions for the advanced Radio Access Network (RAN) of the future must be constructed to be cost-ineffective, enabling the incremental costs reduction on long-run. This is especially valid with the increase of the user applications as well as the Machin to Machine (M2M) traffic within the Internet of Things (IoT) and Artificial intelligence (AI) "era" which is expected to be dominant by 2030. Because of this, it is from highest importance, different incremental cost network deployment strategies to be evaluated and best solution for the Mobile Network Operators (MNO) to be proposed by the end of this decade. In this article, we set special accent on the deployments combining the advanced Wi-Fi standards, as well as the Beyond 5G (B5G) and forthcoming 6G based Radio Access Technologies (RAT), all considered to be part from the Future or 6G-based Wireless & Mobile Heterogeneous Networks (6G-WMHN). Consequently, to our best knowledge, by this contribution we are the first to present a case study for the comparative cost-capacity modeling including the 6G RAT that will deliver significant gains in the spectrum bandwidth and achieved spectral efficiency in bit/s/Hz (1 Petabits/sec of information). The outcomes of this paper present sufficient findings needed one to be able to determine which type of capacity expansion strategy would reduce the aggregated incremental cost, the Net Present Value (NPV) or the total cost of ownership (TCO) for particular expected traffic growth pattern by 2030.

Keywords: *Tera Hertz, Millimeter Wave, 6G, B5G, 5G, LTE-A, IEEE 802.11ax, IEEE 802.11ac, IEEE 802.11n, Incremental Deployment, Incremental Cost, Total Cost of Ownership (TCO), Net Present Value (NPV), Cost-capacity Modeling, Advanced Wireless and Mobile Networks, Heterogeneous Access, Techno-economics Analysis, Machine to Machine (M2M), Artificial Intelligence (AI), Internet of Things (IoT), Cognitive Radio.*

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I. INTRODUCTION

The new high capacity 5G mmW cellular systems are becoming the bearer of the future telecommunications, providing extreme capacity through the huge amount of the available spectrum in the mmW bands (28 GHz - 300 GHz) [1-7]. Nevertheless, the mobile network operators (MNO) continue with their struggle to increase their revenues, to decrease their capital and operational expenditures (CAPEX and OPEX) and to maximize their profitability. Adding to this, that the MNOs already in 2022 started offering unlimited monthly data within the tariff subscriptions, the outcome is that in general mobile and wireless data traffic growth from video usage, device production and application rising interest, as well as from the Machine to Machine (M2M) segment or the Internet of Things (IoT) in which essential role will play the Artificial Intelligence (AI) advances. The IoT it is expected to become a prevalent system in which people, processes, data, and things connect to the Internet and each other, by what there will be 1.8 M2M connections for each member of the global population by 2023 [8]. As a result, it is expected that more than 5 (five) Zettabytes mobile data traffic per month will be transferred by users and machines by 2030 [9].

Based on this, our paper is proposing a techno-economic framework relaying on the discounted incremental costing model that may especially help MNOs to choose from various Radio Access Network (RAN) expansion strategies when trying to satisfy the increasing mobile broadband data traffic demand in the future period of 9 years form 2022 until 2030. Concretely, in this paper for the RAN expansion strategies, we rely our research on the generally accepted industry standard that future mobile networks will be heterogeneous in its nature (HetNet) [10]. We named these networks as Advanced Wireless/Mobile Heterogeneous Access Networks (6G-WMHN), which will be utilizing advanced and novel Radio Access Technologies (RATs), with hierarchically ranged macro (MaBS), micro (MiBS), and other smaller scale base stations (BS) sites, complemented with particular wireless local area network (WLAN/Wi-Fi) Access Points (AP).

About the traffic demand, we consider as input three types of rapid traffic growth scenarios in this period, which are based on: *linear, power* and *sigmoid* growth functions. Considering that the traffic from all three here described scenarios is enormously high (up to 6 Tbps/km2), in this article we decide to analyze the impact on the network cost-efficiency that will potentially arrive with the forthcoming disruptive technologies and approaches that could lead to both architectural and component design to serve as basis for the cellular network from the 6th Generation or, *"6G"*.

According to the [11-14], the frequencies from 100 GHz to 3 THz (Terahertz range) are the resource from potential interest to be considered as capable for talking the enormous mobile broadband data demands. With channels bandwidths of up to 10GHz and superior spectral efficiency, will bring to reality the provisioning of the astonishing data rates from the order of *1.0 Petabits/sec* of information. According to [11] the 6G era is likely to become commercial in the 2025–2035 time frame. Consequently, in our analysis we introduce the 6G RAT as of year 2027. For the period 2022-2026 we also consider multi-RAT approaches designed with the 4G LTE-Advance (LTE-A) RAT for the MaBS and MiBs layers, complemented with the 5G mmW MiBS sites and APs equipped with high speed and advanced IEEE standards like 802.11n, 802.11ac and 802.11ax. Similar as for the 5G mmW, for the 6G THz we consider the installation of the MiBS in the analyzed dense hot-spot urban area of $25{,}000\ user/km^2$.

All these advances into the various RAT to be commercialized by 2030, were our exact motivation to assess their feasibility from techno-economic perspective they to become the main components of the future 6G-WMHN. Hence, in this article by using a case study of incremental cost-based network deployment strategies, we present the comparative cost-capacity modeling of beyond 5G and 6G based WMHN. From the deployment layout mainly based on the BSs with higher ranges, used as reference, we compare in the period of 9 years, different paths to upgrade or introduce new additional BSs/APs sites in the "hot spot" areas for the goal to satisfy the excessive traffic on yearly level. The results present sufficient findings needed one to be able to determine which type of capacity expansion strategy would reduce the aggregated incremental cost or the Total Cost of Ownership (TCO) and more positive Net Present Value (NPV) for certain expected traffic growth pattern. Also, we put special focus on the time component in the research related to the moment when particular investment is done, since a solution that minimizes incremental costs in the short run may be cost inefficient in the long run if traffic demand bursts significantly, and opposite.

This paper consists of 8 sections. Section 2 provides an overview of the most significant related work. Section 3 covers a dimensioning approach of the traffic capacity used. Next, we describe few possible capacity expansion strategies in front of the MNO to be chosen from. Section 5 defines the key parameters of all RATs used in this article. Then, we elaborate the cost modeling with special accent on the incremental deployment aspects. Prior the conclusion section, the results and findings related to the incremental cost analysis are delivered.

II. REVIEW OF LITERATURE

The techno-economic framework presented in this article is a successive stage from our previously published related work on the comparative cost-capacity analysis of the future wireless HetNets e [15-22]. Compared to our previous research, with the approach in this article, but same as in our article [21], we consider capacity expansion strategies as a function of not constant or incremental traffic load. The key differences compared to our article [21] is that in this article we introduce additional and new advanced RATs like the 6G Teraherz at the MiBS layer, as well as the IEEE 802.11ax AP at the smaller cells layer. Furthermore, compared to our research [21] in this case study we introduce more complex traffic growth scenarios, which in all three growth functions (linear, power, and sigmoid) considers severe mobile broadband data loads. Furthermore, with the research in this article we extend the observation period to year 2030, unlike the previous covering the period until 2025. Finally, to our best knowledge, through this article we are the first to present a case study for the comparative cost-capacity modeling including the 6G Teraherz RAT.

Concerning the other authors related work, we base our techno-economic analysis to the references [23-38] covering the various aspects of cost-efficient capacity expansion strategies of HetNets using multi-RAT or multi-BS/AP solutions. We particularly base our incremental cost analysis with non-steady state traffic conditions based on [23, 31, 37]. More precisely, these publications cover the differences between deployments that minimize costs in different time perspectives. Thus, [23] considers for the macro layer the HSPA and in last stage of the time period under analysis only the LTE, where the hotspots are covered by Wi-Fi APs equipped with IEEE 802.11a and IEEE 802.11n equipment. Analysis of cost aspects over time using the LTE RAT in the macro layer complemented with FBS sites and IEEE802.11g and IEEE802.11n for the hot spot layer are covered in [31]. The both, [23] and [31] only consider a single carrier frequency in the macro cellular layer by what the incremental cost estimates presented there could be slightly overestimated. Furthermore, authors in [23] consider two traffic growth scenarios (a conservative and high growth) across the years and [31] and [37] single traffic growth scenarios, by what obtained results for the aggregated incremental cost are more limited from the differentiation point of view. Furthermore, most of the results presented in these papers are based on the use of microwave frequency bands higher than 800 MHz [34] and lower than 2.6 GHz bands and the use of system bandwidth ranging from 5 MHz, 10 MHz [37], 15 MHz, [23], and up to maximum 20 MHz, [27, 28, 31].

As summary, regardless that the approaches in all this related research provides important understandings on the cost-capacity relationship based on the various network deployments, the time variable was not strictly addressed. Consequently, here we focus on the strategies to match the 6G-WMHN deployment over the time or with consideration of the future M2M dominant growing traffic loads.

III. NETWORK CAPACITY DIMENSIONING

For the traffic capacity dimensioning in this paper, we rely on the dimensioning concepts covered into our related contribution [21] and [37]. With this approach the ultimate goal is to assess the Peak area traffic demand in particular geographical area G [Tbps/km^2], for the various traffic growth scenarios in the period 2022-2030 in the 5G, B5G and 6G era. The outcomes from results in this section, will be inputs to assess the TOC and NPV of the various 6G-WMHN incremental deployments presented in the following sections.

With the introduction of 5G nowadays and with further data rates benefits arising from the B5G and 6G RATs, - it is highly expected that the mobile traffic volumes will continue to grow further enormously. According to [8], within the M2M connections category (which is also referred to as IoT), connected home applications will have the largest share and connected car will be the fastest growing application type, or by numbers, connected home applications will have nearly half or 48 percent of M2M share by 2023 and Connected car applications will grow the fastest at 30 % Compound Annual Growth Rate (CAGR) over the forecast period (2018–2023). Certainly, on top of this, also it should be added the traffic produced by the future ultra-reliable and low latency applications user applications (voice, data and multimedia). For this reason, we utilize the *Long-Term-Large-Scale* traffic model, which brings significant accuracy in the targeted area traffic demand in the any moment of time, as shown by the following equation:

$$G(t) = \theta \cdot \beta(t) \sum_k g_k \cdot t_k \text{ [Tbit/s/km}^2\text{]} \quad (1)$$

where $\beta(t)$ represents a typical daily traffic variation in terms of percentage of number of active users for a given time t and g_k and t_k represent the average data rate and the fraction of the subscribers using terminal type k, respectively. For more accurate representation of the findings, we based our results on the *Peak area traffic demand* at the *Busy Hour (BH)*, represented as follows:

$$G \text{ [Tbps/km}^2\text{]} = max_t(G(t)) \quad (2)$$

As per standardized definition, Busy Hour Traffic is determined as percentage of the total daily traffic units obtained during the Busy Hour. With this regard, we consider various values of the indicator $\beta(t)$ representing the number of subscribers which are active during the busy/peak hour. Assuming various levels of BH across the years until 2030, as well as various CAGR levels, then various ratios of heavy versus regular users, as well as different type of end-user devices including the M2M traffic, too, in this article we consider the following three traffic growth scenarios:

1. *High Demand Scenario* – Linear Mobile Data Traffic Growth. Linear growth means that the data traffic as variable grows by the same amount in each time step.
2. *Very High Demand Scenario* – Mobile Data Traffic Growth based on Power function fitting. In our case we assume an n exponential function in the growth of the traffic, by 1.5 times increment every next year.
3. *Extreme Demand Scenario* – Mobile Data Traffic Growth based on "*S-curve*" or Sigmoid shape function. For the period 2025-2030, we assume two times lower CAGR, as we expect the growth of the devices to slow down in the last period of the observation, what is especially valid for the growth trends following the sigmoid function.

For each of these three scenarios, based on the [39], [9], we consider the following four traffic sources from: Smartphones, Smart devices (e.g., Laptops, Tablets) and M2M. Apart from the M2M, for each of these devices we determine fraction of the users t_k using certain terminal type k (i.e., $t_{PC}, t_{tablet}, t_{smartphone}$). We consider that a single user may use more than one device, by what the number of devices also adding the M2M will be higher than the number of users in certain geographical area. Neglecting the diminishing contribution into the data traffic of the feature phone devices, according to [8], [9], [40], and [41] the following key estimates can be drawn for the future of mobile data traffic demand:

- by 2026, the smartphones will contribute with 77.6% in 2025 and the smart devices share will reach 17.1% in 2030;
- the global M2M subscription will reach 97 billion by 2030;

- the traffic volume consumed by M2M services will be 7% of the total in 2020 and 12% of the total in 2030.
- Mobile traffic (without M2M traffic) is estimated to grow at an annual average rate (Compound Annual Growth Rate (CAGR) of around 54% by 2030;
- mobile traffic (including M2M traffic) will be growing at an annual average rate (CAGR) of around 55% by 2030.
- mobile traffic per subscriptions per month is estimated to grow at an annual average rate (CAGR) of around 47% by 2030;
- It is estimated that each subscriber will consume from 12.1 GB in 2022 to 39.4 GB of data traffic per month in 2025 in average and this amount will be around 257 GB in 2030;
- Video traffic will be 4.2 times than non-video in 2025 and 6 times in 2030.
- The forecast model, modelled with an S-curve, predicts possible mobile broadband traffic growth on global scale between 26-times and 70-times from 2020 to 2030.
- Smartphones continue to be at the epicenter of this development as they generate most of the mobile data traffic today – about 97 percent – a share that is projected to increase throughout the forecast period until 2030.
- Globally, the average usage per smartphone is 11.4GB. In 2027, average traffic usage per smartphone is expected to reach 53GB/month in North America.
- The monthly global average usage per smartphone will reach 11.4GB by the end of 2021 and is forecast to reach 41GB by the end of 2027.
- The fastest growing mobile device category is M2M followed by smartphones. The mobile M2M category is projected to grow at a 30 percent CAGR from 2018 to 2023. Smartphones will grow at a 7 percent CAGR within the same period.
- M2M connections will be half of the global connected devices and connections by 2023. The share of Machine-To-Machine (M2M) connections will grow from 33 percent in 2018 to 50 percent by 2023. By 2023, M2M connections will be half or 50 percent of the total devices and connections.
- Smartphones will grow the second fastest, at a 7 percent CAGR (increasing by a factor of 1.4).
- PCs will continue to decline (a 2.3 percent decline) over the forecast period. However, there will more PCs than tablets throughout the forecast period and by the end of 2023 (1.2 billion PCs vs. 840 million tablets).

Based on these assumptions, the Figure 1 and Figure 2, summarizes the inputs for the traffic growth scenarios, related to the overall connection shares between users and M2M, as well as the shares between the Smartphones and Smart devices like tablets, PCs, and laptops in the period 2022-2030.

For the sake of simplicity, we totally neglect the non-smart devices as irrelevant for the mobile broadband data traffic, by what we assume that the mobile data load is fully divided between the smartphones, smart devices and M2M which are the only three type of mobile data generating devices considered in the future until 2030. Based on all these metrics we study different assumptions for each of the three traffic growth scenarios. Thus, we assume that that *h%* of the subscribers are categorized as heavy users, the average daily data rate for terminal *k* can be defined as:

$$g_k = \left[h \cdot g_k^{heaavy} + (100 - h)\, g_k^{regular}\right] / 100 \qquad \text{[Gbit/s]} \qquad (3)$$

Here g_k^{heaavy} [Gbit/s] and $g_k^{regular}$ [Gbit/s] represent the hourly average data rate of a heavy and an regular user, respectively, what can be calculated based on the estimated hourly average usage of a heavy and a regular user G_k^{heavy} [GB/hour] and $G_k^{regular}$ [GB/hour], based on the following equation:

$$g_k^{heavy\ /\ regular} = G_k^{heavy\ /\ regular} \cdot 1024 \cdot \frac{8}{3600} \qquad \text{[Gbit/s]} \qquad (4)$$

Unlike [37] and as presented in [21], we will consider also growth of the β_{MAX} value across the 9 years period from 2022 until 2030. It should be noted that for the θ we consider constant and very high density in BH of $25{,}000\ user/km^2$ representing a hot-spot area of Xidan area in the capitol city of Beijing, China, as per the historical data provided by current networks of Chinese operators for 2020 [9].

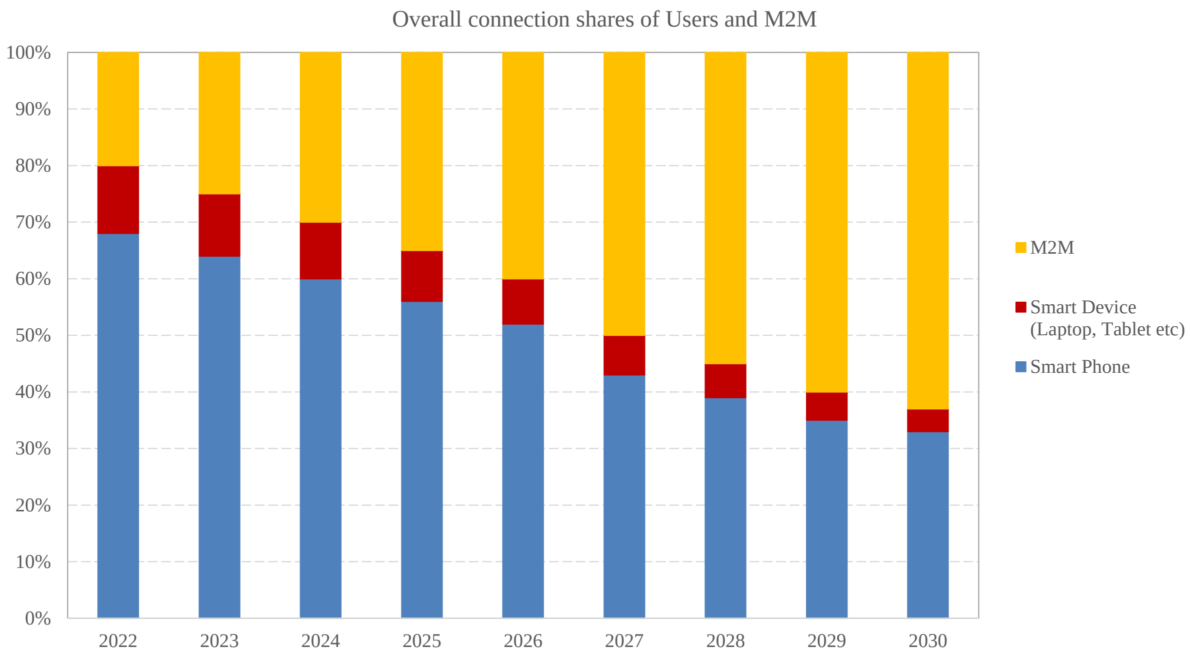

Figure 1: Shares between the users and machines from the overall connections until 2030.

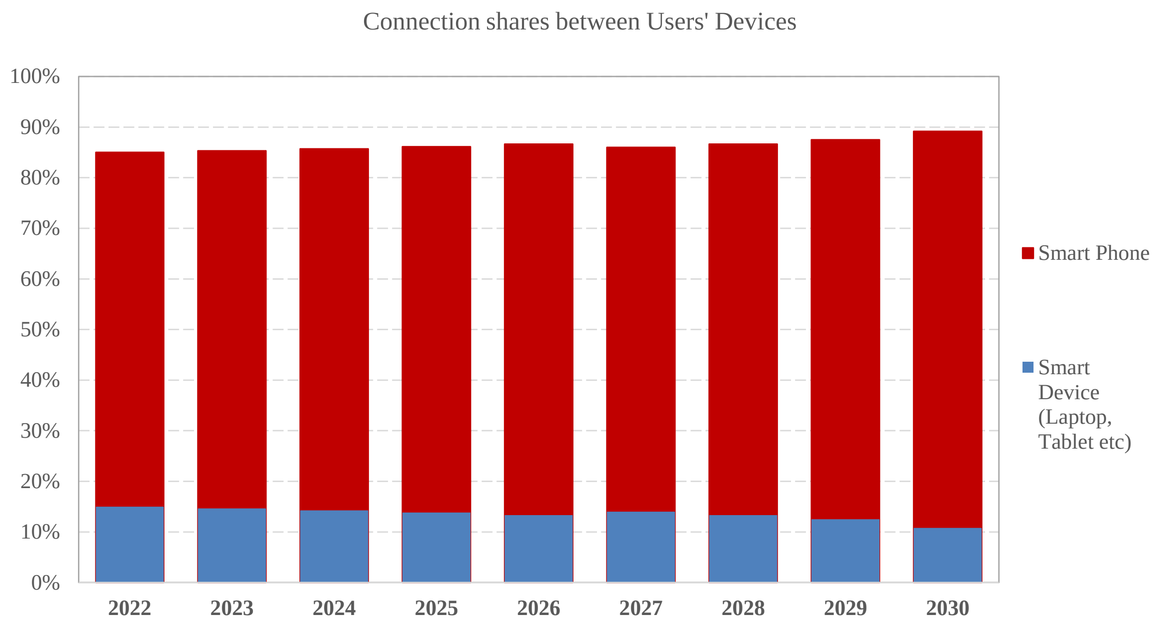

Figure 2: Shares between the Smartphone and Smart devices used by end-users until 2030.

Consequently, Table 1 summarizes the conversions of the various considered load/user/month to the user data rates (Mbps) in line with (5):

$$C_{AREA} = R \cdot \rho_{AREA} \qquad [\text{Tbps/km}^2] \qquad (5)$$

where, R denotes the demanded data rate per user (Gbps/user) and $\rho_{(bus/res)}$ (users/km²) the user density. As it can be seen, it is shown all the estimated values used as input for the Power Growth Scenario, for the Smartphones, Smart Devices and M2M, resulting in the overall area capacity within the last column. Furthermore, the resulting average area throughput on downlink for the three traffic growth scenarios is presented in Figure 3.

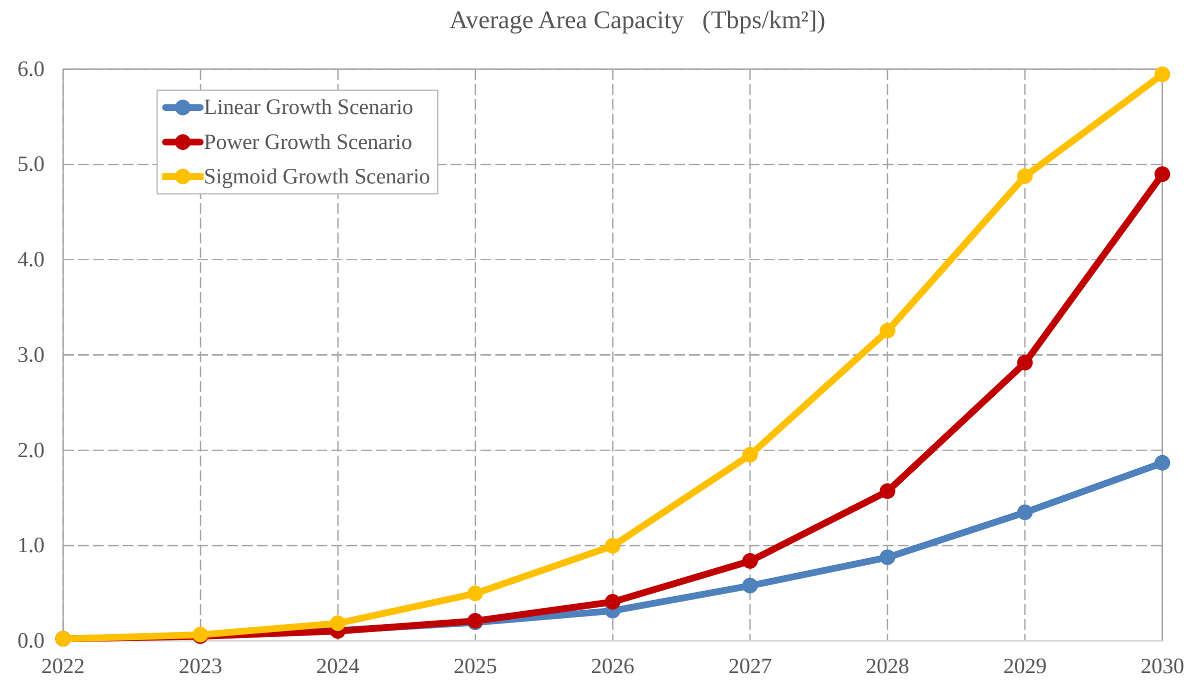

Figure 3: Average area capacity for the three traffic growth scenarios.

Table 1 Detailed estimation parameters for the Incremental total capacity generated in the hot-spot urban area in the Xidan area of the capitol city of Beijing, China, for the Power Growth Scenario in the period 2022-2030.

		Smartphone			Smart Device			M2M					
Year of analysis	Share of heavy ysers (h %)	Monthly mobile data (Gk [GB/monlht]	Average data rate gk (Mbps)	Users share (tk %)	Monthly mobile data (Gk [GB/monlht]	Average data rate gk (Mbps)	Users share (tk %)	Monthly mobile data (Gk [GB/monlht]	Average data rate gk (Mbps)	M2M Contirubtuin in ovreall connections (%)	User density per km2	Lamda Max (Busy Hour)	Area Capacity (Tbps/km2)
2022	50%	50	2.1	85.0%	300	12.8	15.0%	26	1.1	20%	25,000	20%	0.02
2023	55%	75	3.4	85.3%	450	20.693333	14.7%	40	1.8	25%	25,000	30%	0.05
2024	60%	113	5.5	85.7%	675	33.28	14.3%	59	2.9	30%	25,000	40%	0.11
2025	65%	169	8.9	86.2%	1013	53.28	13.8%	89	4.7	35%	25,000	50%	0.22
2026	70%	253	14.2	86.7%	1519	84.96	13.3%	133	7.5	40%	25,000	60%	0.43
2027	75%	380	22.5	86.0%	2278	135	14.0%	200	11.9	50%	25,000	70%	0.88
2028	80%	570	35.6	86.7%	3417	213.84	13.3%	300	18.8	55%	25,000	80%	1.65
2029	85%	854	56.3	87.5%	5126	337.77	12.5%	450	29.7	60%	25,000	90%	3.06
2030	90%	1281	88.7	89.2%	7689	532.17	10.8%	675	46.7	63%	25,000	95%	5.13

IV. RADIO ACCESS NETWORK MODELING

The techno-economic analysis of this paper is based on illustrated Beyond 5G and 6G RAN Architecture of 6G-WMHN illustrated in Figure 4. As per this envisaged architecture, its combines various single or multi–Radio Access Technologies (RATs) with hierarchically ranged macro (MaBS), micro (MiBS), pico (PBS) and femto (FBS) base stations (BS) sites, complemented with certain wireless local area network WLAN or Wi-Fi AP. For the sake of simplicity in this article we will limit our analysis to the MiBS level. As it can be seen, the architecture also considers the 6G Teraherz based MiBS small cells, too.

Authors in [10] outlined that the 5G and B5G networks will be HetNets that consist of nodes/cells with heterogeneous characteristics and capacities, which will result in a multi-tier architecture. Today's and HetNets from the near future (utilizing RATs like 4G LTE-Advanced) "live" with limited microwave spectrum. According to [1], the "millimeter wave (mmW) interface", is considered as one of the five potentially disruptive technologies and approaches that could lead to both architectural and component design to serve as basis for the fifth generation (5G) cellular network. The authors of the [2-7], have presented significant methodologies for new mmW systems, utilizing the huge amount of the available spectrum in the mmW bands (28 GHz - 300

GHz). Furthermore, the analysis conducted in [11] shows that Terahertz frequencies will likely be the first wireless spectrum that can provide the real time computations needed for wireless remoting of human cognition, what is required for the B5G and even 6G networks. Articles [11, 13, 14] are extensively covering the concept and aid in the development and implementation of the sixth generation (6G) of wireless networks, and beyond. They conclude that frequencies from 100 GHz to 3 THz are promising bands for the next generation of wireless communication systems because of the wide swaths of unused and unexplored spectrum. With this regard, also from the high consideration is the WLAN deployment as complimentary RAT, related to what we consider the following three standards of IEEE: 802.11n, 802.11ac and 802.11ax.

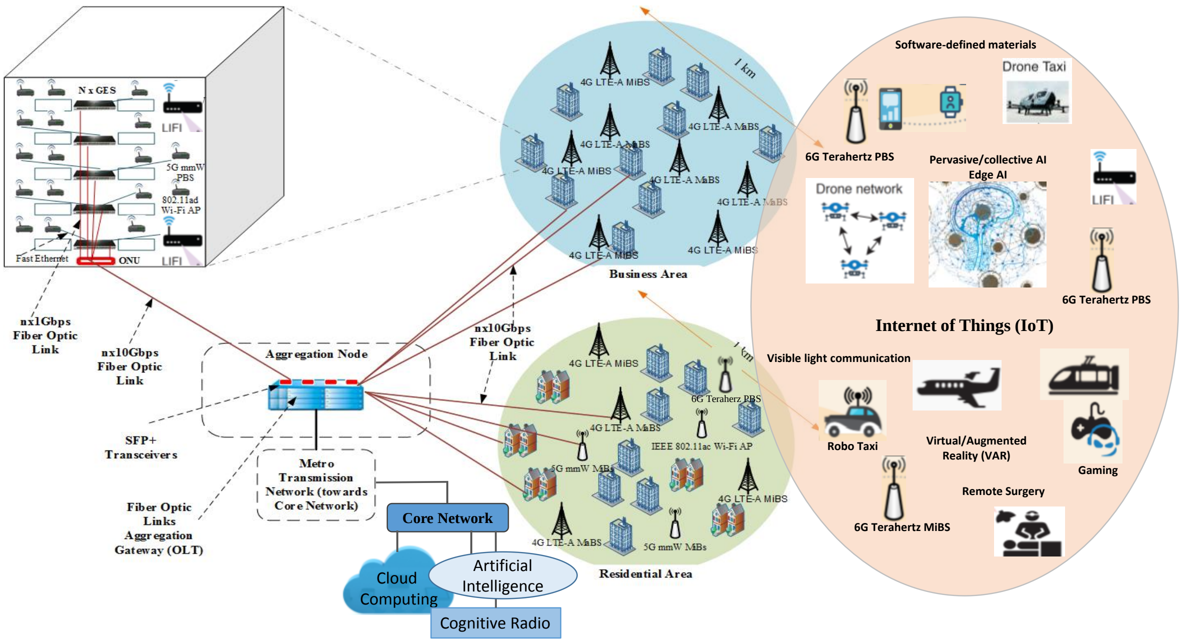

Figure 4: 6G-WMHN RAN Deployment Scenarios Architecture.

A particular MNO may consider various expansion strategies of its RAN, when trying to respond to the demand as per the three traffic growth scenarios elaborated in Section 3 above. According to [23] and our contribution [21], we consider the following three expansion paths:

1. Expansion strategy considering both cellular and WLAN RATs, or so called *"Multi-RAT"*, where the 4G-LTA, 5G and 6G RAT cells, are complemented with certain type of IEEE Wi-Fi standard enabled Access Point (AP).
2. Expansion strategy considering cellular only *"CE-ON1"* RATs combining 4G-LTA, 5G and 6G RAT cells, by which the 5G MiBS and 6G MiBS will be built on new independent sites.
3. Expansion strategy considering cellular only *"CE-ON2"* RATs combining 4G-LTA, 5G and 6G RAT cells, but in this case by consideration of site reuse, or 5G from 4G MiBS site reuse and the 6G MiBS on the same site built for the 5G MiBS.

The dimensioning in all the three expansion strategies is based on goal to build enough base stations from particular type and RAT in certain year in order to cover the growth of the traffic (marked as "δ ") compared to the traffic level in the previous year, certainly by consideration of one of the three capacity growth scenarios elaborated in the Section 3. Also, for all three expansion strategies, the 5G based cells are introduced as of 2022, and 6G as of year 2027.

For the "Multi-RAT" expansion strategy, a 4G LTE-A is considered to be starting layout which in 2022 will be combined with the first 5G MiBS sites. Then, in 2023 the "δ " traffic is handled by adding the new sites with the IEEE 802.11n enabled sites. In 2024, on the same sites the "δ " traffic will be covered with the IEEE 802.11ac enabled sites. In 2024 and 2025 on the same sites build for the previous years WLAN, it is added new RAT with the IEEE 802.11ac type of access points. In the same within the period of four years, 2023-2026, every year a new carrier of the 5G MiBS sites is added at the same sites. Finally, in year 2027 an 6G RAT is introduced via the upgrade of the 5G MiBS sites with 1 x 6G MiBS carrier. Within the period 2028-2030, it is ass and additional 6G carrier is added on the existing MiBS sites.

Related to the *"CE-ON1"* and *"CE-ON2"* expansion strategies, we consider that the deployed 4G LTE-A MiBS in 2022 will be enriched with 1 carrier 5G MiBS in the same year. Now, the yearly "δ " traffic will be covered by adding single carrier of 5G MiBS per year until 2026, and from 2027 the yearly traffic increment will be treated by the 6G MiBS expanded with new single carrier each year until 2030. The difference between these two cellular only scenarios is that for the *"CE-ON1"* we consider all new sites for the yearly acceptance of the traffic incremental "δ ", and for the *"CE-ON2"* we envisaged the site reuse for the whole period 2022-2030. Table 2, summarizes the presented expansion strategies for an mobile network operator up to the year 2030.

Table 2 Multi-RAT and cellular deployment strategies to handle the incremental traffic capacities (abbreviation "c." stands for "carrier").

Expansion Strategy	*Multi-RAT*	*CE-ON1 (all new sites)*	*CE-ON2 (sites reuse)*
2022	LTE-A MaBS (5c) +5G MiBs (1c)	4G Mibs (1c) + 5G MiBs (1c)	4G Mibs (1c) + 5G MiBs (1c) upgrade at 4G MiBs site
2023	+5G MiBs (+1c, tot. 2c) + WiFi 802.11n new site	+5G MiBs (+1c, tot. 2c)	+5G MiBs (+1c, tot. 2c) site reuse
2024	+5G MiBs (+1c, tot. 3c) + WiFi 802.11ac at same site	+5G MiBs (+1c, tot.3c)	+5G MiBs (+1c, tot.3c) site reuse
2025	+5G MiBs (+1c, tot. 4c) +WiFi 802.11ax at the same site	+5G MiBs (+1c, tot. 4c)	+5G MiBs (+1c, tot. 4c) site reuse
2026	+5G MiBs (+1c, tot. 5c) +WiFi 802.11ax at the same site	+5G MiBs (+1c, tot. 5c)	+5G MiBs (+1c, tot. 5c) site reuse
2027	+6G MiBS (1c) upgrade at 5G MiBs site	+6G MiBS (1c) new site	+6G MiBS (1c) upgrade at 5G MiBs site
2028	+6G MiBs (+1c, tot. 2c)	+6G MiBs (+1c, tot. 2c)	+6G MiBs (+1c, tot. 2c) site reuse
2029	+6G MiBs (+1c, tot. 3c)	+6G MiBs (+1c, tot. 3c)	+6G MiBs (+1c, tot. 3c) site reuse
2030	+6G MiBs (+1c, tot. 4c)	+6G MiBs (+1c, tot. 4c)	+6G MiBs (+1c, tot. 4c) site reuse

V. KEY PARAMETERS OF THE RADIO ACCESS TECHNOLOGIES (RAT)

For all BS/AP classes considered, the site coverage is dimensioned as circle area ($A = \pi\ r^2$). According to [30], we model aggregated system capacity, T_{syst}, as follows:

$$T_{syst} = W \cdot N_{site} \cdot N_{cell} \cdot S_{eff} \qquad (6)$$

where W is allocated bandwidth in MHz, N_{site} is the total number of BS/AP sites within the system coverage area, N_{cell} is the number of cells and S_{eff} is the cell average cell spectral efficiency in bps/Hz/cell.

According to [42], the IMT-Advanced UMa model considers inter-site distance of 0.5 km for MaBS. We assume 0.25 km cell range for the 4G LTE-A MaBS sites and 0.1 km cell range for the 4G LTE-A MiBS and 5G mmW MiBS sites because we assume it is deployed according to the 3GPP Urban Micro (UMi) model [42], too. This is in line with the elaborations in [2-5], where authors also estimate 0.1 km range for 3-sector 5G mmW MiBS site. For the sake of simplicity, we consider that the 6G THz MiBS will have the same coverage range as the 5G mmW MiBS.

Table 3: Coverage and capacity KPIs for different RAT type of BSs/APs classes.

BS/AP Class RAT Parameter	4G LTE-A MaBS	4G LTE-A MiBS	5G mmW MiBS	6G THz MiBS	Wi-Fi IEEE 802.11n AP	Wi-Fi IEEE 802.11ac AP	Wi-Fi IEEE 802.11ax AP
Range (km)	0.25	0.1	0.1	0.1	0.03	0.03	0.03
Coverage (km²)	0.2	0.03	0.03	0.03	0.003	0.003	0.003
Sectors	3	3	3	3	1	1	1
Carriers	1	1	1	1	1	1	1
Bandwidth (MHz)	20	20	500	10000	34.4	80	80
Carrier (GHz)	2.6	2.6	28	3000	5	5	6
Av. Cell Spectral Eff. (bps/Hz)	3.8	4.2	3.38	10.8	8.37	16.25	15.0
Av. Cell Capac. (Mbps)	76	76	1690	108000	228	866	1200
Av. Site Capac. 1-3 sectors (Mbps)	228	252	5070	324000	288	866	1200

Considering the best antenna configuration, based on [43] the average cell spectral efficiency for LTE-A is 4.2 and 3.8 bit/s/Hz/cell for the microcellular and base coverage urban environments, respectively. The cell edge spectral efficiency equals to 0.15 and 0.10 for the FDD UMi and FDD Uma (20 MHz carrier), respectively. Based on the empirical results of [2-5], for the mmW we consider average cell spectral efficiency of 3.34 bit/s/Hz/cell and 2.93 bit/s/Hz/cell when using 28 GHz and 73 GHz carriers, respectively. In this case, the 5%

cell edge rates are 52.28 Mbps and 24.08 Mbps when using 28 GHz and 73 GHz single carriers, respectively. Regarding the bandwidth, for the 4G LTE-A RAT we consider for each bandwidth chunks of 10 or 20 MHz and for the 5G mmW system in line with [2], [5] and [7], we consider the 50-50 UL-DL TDD split of the 1 GHz bandwidth (or 500 MHz chunk in DL).

We consider that the future 6G RAT are 5-10 years away from implementation, and that will benefit from the operation into THz frequency band, which is from 100 GHz through 3 THz, [44-46]. In this band an enormous data rates are expected to be achieved. According to [11, 12], Future wireless generations (e.g., 6G or 7G) are likely to allocate up to 10 GHz RF channels for each user in the THz regime, and by assuming that each user is able to exploit 10 bits/symbol modulation methods (or spectral efficiency of 10.0 bit/s/Hz) and 1000 times increase in channel capacity using yet-to-be-invented concepts beyond cooperative multipoint (CoMP) and Massive-MIMO, it is readily seen that data rates of 100 Terabytes/sec will be achieved.

For the Wi-Fi coverage-capacity deployment options, we consider that according to [47] it is very difficult to exceed 50-60% of the nominal bit rate of the underlying physical layer of Wi-Fi. In line with [23] the IEEE 802.11n standard envisages 34.4 MHz channel bandwidth at 5.2 GHz carrier frequency with the maximum physical layer data rate of 288 Mbps. According to [40], the IEEE 802.11ac products operating in the 5 GHz band with 80 MHz, with up to 30 m coverage range. According to [48], the maximum speed of a single 802.11ac stream is roughly 866Mbps, whereas a single stream of 802.11ax WiFi is 1.2Gbps.

According to all the above analysis in this section, the next Table 3 summarizes the coverage-capacity estimates in line with [43], [2] [4-7], [47, 49, 50].

VI. MODELING THE INCREMENTAL COSTS OF THE NETWORK

In this section, we consider the “up to date” initial and running cost estimates of various BS/AP classes for the period 2022-2030. Based on demanded capacity and coverage targets elaborated previously, it is forthright to estimate the number of BS/AP sites ($N_{BS/AP}$) which multiplied with CAPEX figures per BS/AP class ($C_{BS/AP}$), very closely yields the total CAPEX needed for deployment of particular 6G-WMHN layout, or:

$$CAPEX_{AWM-HAN} \approx C_{BS/AP} \cdot N_{BS/AP} \quad (7)$$

A BS of class *i* is associated with cost c_i, including capital expenditures (CAPEX) and operating costs (OPEX). We consider the BS equipment, BS (site) installation & buildout, backhaul transmission equipment and Radio Network Controller (RNC) equipment as BS related CAPEX items and electric power, operation & maintenance, site lease and backhaul transmission lease as BS related OPEX items. We base our cost structure modelling to the methodology developed in [9, 15, 21, 22]. The total network cost comprising of radio access network (C_{RAN}) related costs, business-driven ($C_{BUS/COM}$) costs and costs for spectrum license (C_{SPEC}) normalized per unit area (A_{SYS}), can be presented as follows:

$$C_{TOT} = C_{RAN} + C_{BUS/COM} + \frac{C_{SPEC}}{A_{SYS}} \quad [\frac{\cos t}{area}] \quad (8)$$

In this chapter, we diminish the spectrum and business related costs as sunk cost. The present values of the RAN related cost or the total accumulated Net Present Value of the network (*NPV (C_{TOT})*) represents the sum of the yearly cost in terms of annualized CAPEX and OPEX, which are discounted by discount rate of 12.5% (we equalize the discount rate to the Weighted Average Cost of Capital – WACC [31]), for the network life cycle of K = 10 years, or:

$$NPV(C_{TOT}) = NPV(OPEX) + NPV(Ann.CAPEX) \quad (9)$$

Furthermore, based on this cost modeling approach, the primary goal is to answer the question, which type of capacity expansion would minimize aggregate incremental cost or the Total Cost of Ownership (TCO) (for an expected traffic growth). According to [31], TCO should be used for offering a clear picture over the total involved costs for the entire studied period by taking into account the total expenses when running a network including acquisition price and yearly operating & maintenance costs.We consider the BS equipment, site installation & buildout, backhaul transmission as BS related CAPEX items and electric power, O & M, site lease and transmission lease as BS related OPEX items. . In line with [23], [31], in this study new base stations and upgrades of existing sites are deployed over time, because of what an annual price erosion should be considered for base station equipment.

Table 4: Initial Cost drivers with respect to CAPEX and OPEX for newly BS/AP classes deployed in concrete year (the reuse of the site is indicated).

New sites	CAPEX (k€)			OPEX (k€)		
BS/AP Class/RAT	Radio Eq.	Trans.	Site	Trans.	Site	O&M, Power
4G LTE-A MaBS - 3 sector and 3 carriers	30.0	30.0	30.0	15.0	10.0	9.0
4G LTE-A MaBS - 3 sector and 1 carrier	10.0	30.0	30.0	10.0	10.0	6.0
4G LTE-A MiBS - 3 sector and 3 carriers	15.0	30.0	10.0	15.0	5.0	2.5
4G LTE-A MiBS - 3 sector and 1 carrier	5.0	10.0	10.0	10.0	5.0	1.5
5G mmW MiBS - 3 sector and 3 carriers	12.8	30.0	8.0	15.0	5.0	2.5
5G mmW MiBS - 3 sector and 3 carriers (site reuse)	12.8	30.0	0.0	15.0	0.0	2.5
5G mmW MiBS - 3 sector and 1 carrier	4.3	10.0	8.0	10.0	5.0	1.5
6G THz MiBS - 3 sector and 1 carrier	6.7	30.0	10.0	15.0	5.0	5.0
WLAN 802.11n AP – 1 sector and 1 carrier	3.8	3.0	1.0	2.0	0.0	0.75
WLAN 802.11ac AP - 1 sector and 1 carrier	3.4	5.0	1.0	3.0	0.0	0.75
WLAN 802.11ax AP - 1 sector and 1 carrier	4.1	5.0	1.0	3.0	0.0	0.75

In this article we consider the cost of 30 k€ for the 4G LTE-A RAT MaBS radio equipment supporting three carriers and three sectors. This would mean that price of additional transceivers per sector per carrier frequency is around 3.4 k€, or around 2/3 cheaper than the price for additional transceivers considered of 5.0 k€ in year 2007 in [23]. Further, based on the findings in [23], that price of a MiBS and PBS equals 50% and 15%, respectively of a single-carrier MaBS, we yield that radio cost will be around 15 k€ and 12 k€ for the MiBS and PBS supporting three carriers and three sectors with 4G LTE-A RAT, respectively. We consider 50% reduction in the 5G mmW MiBS radio equipment, by what we obtain 8.0 k€ and 6.0 k€ for the 5G mmW MiBS and PBS respectively. For the year 2007, authors in [23] estimate 5.0 k€ for the installation of the transmission at MaBS site and 5-7 k€ for the annual OPEX related to transmission. We consider the annual cost for transmission of 15 k€, as for the year 2013 the authors in [31] consider 10 k€. The [28] considers around 80 k€ for the MaBS in rural area and around 30 k€ for the MaBS in urban area. According to [31], for year 2010, this cost was estimated to be 10 k€ and the same price is considered in the [31] with lowering of 25% after period of 7 years (5% price erosion on yearly level). Authors in [31] consider the annual OPEX of 10 k€ for the MaBS site lease, what will be our estimate, too. With this regard, we consider the same OPEX related to annual operations and maintenance (O&M) and power consumption as estimated in [31], or 10 k€ and 5 k€, respectively. We model all other CAPEX and OPEX drivers of MiBS and PBS site compared to MaBS in line with the ratios outlined in [23], but we consider higher transmission related costs. Regarding the Wi-Fi APs, as benchmark we use the IEEE 802.11ac products of around €160 [51] or 2.5 k€ per AP for the CAPEX and for the OPEX 5.0 k€.

Regarding the mmW based deployments, it should be noted that such hardware is far from commercialization so the price level is quite uncertain. Nevertheless, due to general declining trend of the prices for the BS related hardware, we expect that the radio equipment for the 5G mmW sites to be lower compared to 4G LTE-A RAT. Thus, considering the 5% yearly price erosion, we assume that the 5G mmW MiBS radio equipment supporting 3 sectors and 1 carrier, will be around 12.8 k€ for the reference year 2021. Quite opposite, because of the need to support the RAN capacity advances, we assume the transport cost for the typical PTP backhaul infrastructure to have an increasing trend.

The findings related to the cost items (CAPEX and OPEX) for 4G LTE-A MaBS, 4G LTE-A MiBS, 5G mmW MiBS sites and Wi-Fi AP sites are elaborated in detail in our contribution [20] which is based on the cost items analysis from [23, 27, 28, 31, 50, 52]. Based on this we assume to applicable the same cost items for the 802.11ax as for the 802.11ac, as well as, the same for the 6G THz MiBS like for the 5G mmW MiBS. As summary, Table 4 contains the cost drivers with respect to CAPEX, OPEX and total discounted costs for each of the newly deployed BS/AP classes enabled with various RATs. Finally, for the upgrade of the existing site, Table 5 summarizes the exact assumptions on incremental costs per unit for each of the particular expansion strategies considered in the Table 2 (M-RAT, CE-ON1 and CE-ON2). Transmission costs are considered to be stable or higher across the years due to the higher peak data rate required in the future. Nevertheless, with the introduction of 6G as of 2027 we consider that even reused sites, will need much significant increase of the CAPEX and OPEX for the transmission from the BS to the backhaul/core network.

Table 5: Estimates on the incremental cost per BS/AP class for upgrades of existing sites, in the reference year, for particular expansion strategy.

BS/AP Class/RAT -Upgrades of existing sites	CAPEX (k€)			OPEX (k€)		
	Radio Equipment	Transmi-ssion	Site	Transmi-ssion	Site	O&M, Power
Dense 4G LTE-A MaBS - 3 sector and 1 carrier	10.0	0.0	30.0	10.0	10.0	6.0
Dense 4G LTE-A MaBS - 3 sector and 3 carriers	30.0	0.0	10.0	15.0	0.0	6.0
4G LTE-A MaBS - 3 sector and 1 carrier, upgrade with additional carrier	10.0	0.0	0.0	10.0	0.0	0.0
4G LTE-A MiBS - 3 sector and 1 carrier, upgrade with additional carrier	5.0	0.0	0.0	10.0	0.0	0.0
5G mmW MiBS - 3 sectors and 1 carrier (upgrade with site reuse)	4.3	5.0	0.0	10.0	5.0	0.0
5G mmW MiBS - 3 sectors and 1 carrier (upgrade of BS platfrom for hot spot)	4.3	5.0	0.0	10.0	2.0	0.0
5G mmW MiBS - 3 sector and 1 carrier, upgrade with additional carrier	4.3	0.0	0.0	10.0	0.0	0.0
Dense 5G mmW MiBS 3 sectors and 3 carriers	12.8	0.0	8.0	10.0	5.0	2.50
Dense 6G THz MiBS - 3 sector, 1 carrier, site reuse	6.7	20.0	0.0	15.0	0.0	5.00
WLAN 802.11ac AP - 1 sector and 1 carrier	3.1	3.0	0.0	2.0	0.0	0.25
WLAN 802.11ax AP - 1 sector and 1 carrier	4.1	3	0.0	2.0	0.0	0.25

VII. RESULTS, ANALYSIS AND DISCUSSIONS

Based on the inputs from the previous sections, in this section, we are presenting the simulation results for the TCO and NPV of the three expansion strategies (Multi-RAT, CE-ON1 and CE-ON2) for each of the considered mobile broadband traffic growth scenarios (LINEAR, POWER and SIGMO) in the period of 9 years from year 2022 to year 2030. To confirm, as elaborated earlier in this paper, the cost analysis is based on comparing the total cost for each deployment in order the MNO to be able to accept the targeted capacity demand for particular year. The related discounted incremental costs for each deployment scenarios are shown on the Figure 5.

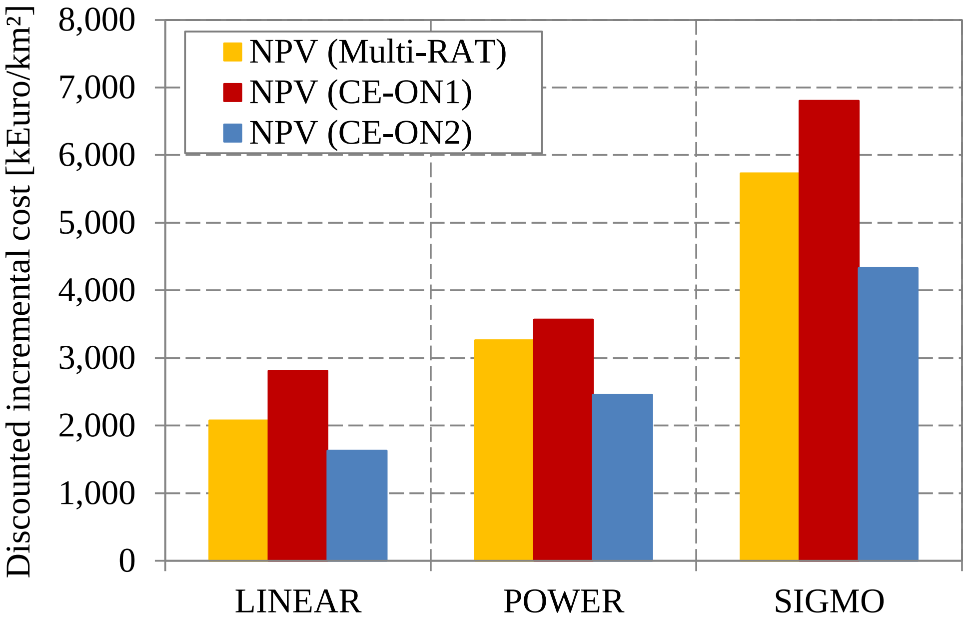

Figure 5: The Net Present Values (NPVs) of the incremental cost for the expansion strategies related to various traffic growth scenarios, discounted until 2030.

From the presented results it can be concluded that for all three traffic growth scenarios, the lowest NPV is coming with the CE-ON2 expansion strategy, being around 1.8, 2.2 and 4.2 Mil€/km² for the liner, power, and sigmoid function traffic growth cases, respectively. The reason for this is that the site reuse strategy is showing significant lower capital expenditures, compared with the strategy considering only the new sites like CE-ON1, or Multi-RAT having combination between the new and site reused.

Thus, the CE-ON1 expansion strategy is showing the highest total discounted incremental cost for all three traffic growth scenarios, even though it is similar at around the 3.3 Mil€/km² with the Multi-RAT deployment at the power-function based capacity growth curve. Certainly, it needs to be concluded that even in the case of the CE-ON2 expansion strategy the NPV is rather high reaching around 4.2 Mil€/km² for the sigmoid function-based traffic growth, especially that with the introduction of the 6G RAT it will be required a significant increase into the transmission increase what will bring also a higher operational expenditure on yearly level. In all three traffic growth scenarios, it is clear that CE-ON2 expansion strategy is lowering the NPV for around 30-40% compared to CE-ON1 and for 10-20% compared to the Multi-RAT expansion strategy.

Regarding the Multi-RAT expansion strategy, it can be seen that despite the power function-based traffic growth is brining more expensive incremental deployment, it is just above 1 Mil€/km² more expensive compared to the liner traffic growth, due to the fact that the Multi-RAT strategy especially in the initial period of few years is relying of the more expensive and CAPEX driven LTE-A technology for macro and micro base stations, before the higher shift is achieved towards the 5G and advanced Wi-Fi RATs like IEEE 802.11ac and 802.11ax.

Related to the total number of used BS/AP sites in hot spots per km², the findings for each of the considered expansion strategy and traffic growth scenarios are summarized in Table 6. From these figures it can be concluded that higher number of BS/AP sites is required in the period 2024-2026, due to the enormous growth expected for all three traffic growth scenarios within this period from one side, and from other side due to the insufficiency of the 5G RAT sides to adequately respond to such growth. Nevertheless, this situation is rapidly changing with the launch of the 6G RAT envisaged for 2027. It can be seen that for the particular area of interested analyzed in this paper maximum 11 sites will be required to cope with the highest traffic growth in 2030 in case of the Multi-RAT scenario. Overall, the 6G RAT with its spectral efficiency and available bandwidth it is expected to decrease the need for the construction of the new sites even for more than10 times.

Going further, the aggregated incremental (non-discounted) expenditures representing the TCO per year are presented in Figure 5-1, 5-2 and 5-3, for all the three traffic growth scenarios). The TCO for the final year (2030) shows the overall costs throughout the entire period under research.

It can be found that in all three traffic growth scenarios, the most TCO is involved with the CE-ON1 expansion strategy. Surprisingly, in year 2030 the TCO for the Multi-RAT is slightly over passing the TCO of the CE-ON1 expansion strategy. From this, one can draw a conclusion that with the introduction of the 6G RAT, the need for the Multi-RAT based expansion is becoming obsolete. This is especially due to the enormous cell capacity coming with the 6G compared to the even most advanced IEEE 802.11 WLANs.

Table 6: Quantity of BS/AP sites per km² required in the hot spot layer to satisfy the excessive “δ “ traffic in particular year.

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030
LINEAR Traffic Growth Scenario									
Multi-RAT	4	7	10	14	21	3	3	5	6
CE-ON1/CE-ON2	4	8	12	18	26	1	1	2	2
POWER Traffic Growth Scenario									
Multi-RAT	4	6	10	18	34	5	8	14	20
CE-ON1/CE-ON2	4	6	12	23	42	2	3	5	7
SIGMO Traffic Growth Scenario									
Multi-RAT	4	9	22	53	84	10	13	16	11
CE-ON1/CE-ON2	4	10	25	65	104	4	5	6	4

With this regard, it can be concluded that the curves are following the same pattern in all three Figures 6, 7 and 8, saying that the TCO is flattened after the introduction of the 6G RAT, which is brining significant hopes for more profitable business on the MNO side as of 2027 onwards. Until 2026, the TCO for the Multi-RAT and CE-ON2 expansion strategies is insignificantly different and it is following the exponential growth pattern. Again, the CE-ON1 expansion strategy is delivering the higher TCO, due to non-utilization of the existing sites, what could be from particular concern if certain MNO can't afford site reuse due to certain reasons.

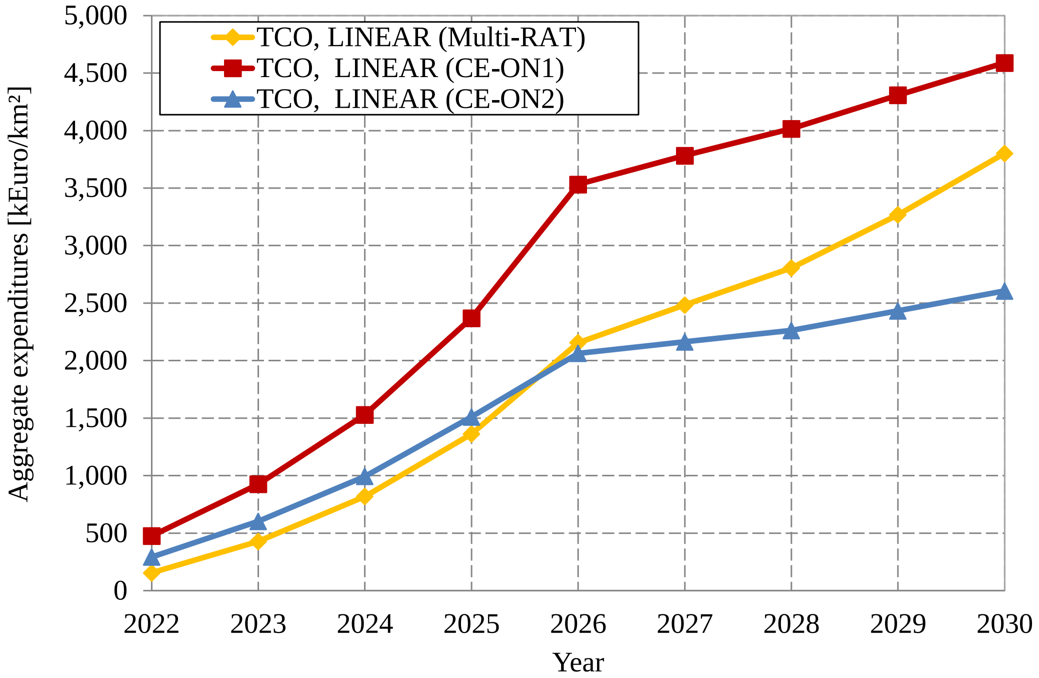

Figure 6: The Total Cost of Ownership (non-discounted) per year for the Linear Traffic Growth Scenario.

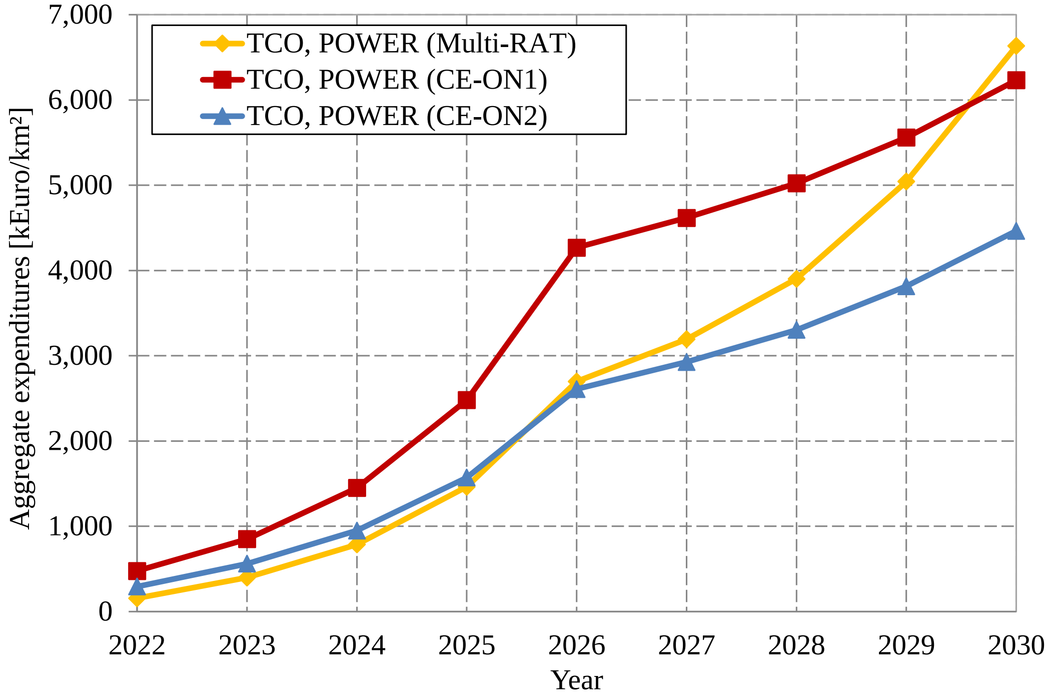

Figure 7: The Total Cost of Ownership (non-discounted) per year for the Power Traffic Growth Scenario.

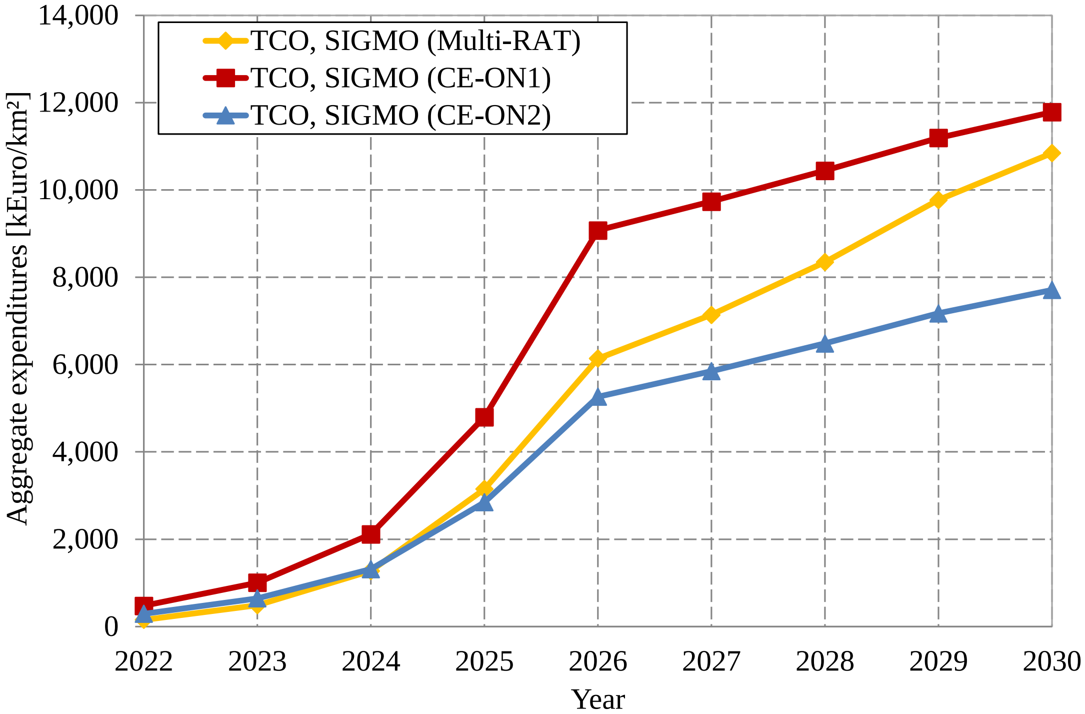

Figure 8: The non-discounted Total Cost of Ownership (TCO) per year for the Sigmoid Traffic Growth Scenario.

VIII. CONCLUSION

In this paper we conduct an extensive survey wit aim to assess the techno-economics capabilities of the existing and future advanced radio access technologies to cost-efficiently respond to the expected enormous data traffic growths, when utilized in the 6G-WMHN. As the mobile broadband traffic demand will continue to grow rapidly, we took into consideration expectations that the M2M traffic will reach 63% from the overall mobile connections by 2030, especially that our living world will become more and more the ubiquitous or IoT world, in which people, processes, data, and things connect to the Internet and each other. We consider three different traffic growth scenarios in the period 2022-2030, bringing high, very high and extreme mobile data user demand, in manner that all three scenarios are following different growth function, or linear, power, and sigmoid, respectively. For all three traffic growth scenarios we analyze and compare the cost-efficiency of 6G-WMHN build with multi-RAT solutions or cellular only solutions. Related to this, the unique contribution of this article is that here we originally propose incremental cost analysis, through determination of aggregate incremental (non-discounted) expenditures per year, or the TCO and NPV, over the longer period of 9 years in the future, based on future advanced RATs like 6G TeraHerz, 5G mmW, IEEE 802.11ax, as well as the current LTE-Advanced, Wi-Fi IEEE 802.11n and IEEE 802.11ac.

Some of the key findings show that the lowest NPV is coming with the CE-ON2 expansion strategy, the reason for this is that the site reuse strategy is showing significant lower capital expenditures, compared with the strategy considering only the new sites like CE-ON1, or Multi-RAT having combination between the new and site reused. Thus, the CE-ON1 expansion strategy is showing the highest total discounted incremental cost for all three traffic growth scenarios. In all three traffic growth scenarios, it is clear that CE-ON2 expansion strategy is lowering the NPV for around 30-40% compared to CE-ON1 and for 10-20% compared to the Multi-RAT expansion strategy.

In prospect of the number of utilized base station sites, the situation is rapidly changing with the launch of the 6G RAT envisaged for 2027. Overall, the 6G RAT with its spectral efficiency and available bandwidth it is expected to decrease the need for the construction of the new sites even for more than 10 times compared to nowadays 4G and 5G RATs. Furthermore, after the introduction of the 6G RAT also the TCO is flattened on long run, which is brining significant hopes for more profitable business on the MNO side as of 2027 onwards.

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