# The Long Road to Sobriety: Estimating the Operational Power Consumption of Cellular Base Stations in France

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***Abstract*—As the Information and Communication Technology (ICT) sector represents 1.8% to 3.9% of the global Green House Gas (GHG) emissions, it is of upmost importance to know how much energy is spent annually in mobile networks and how this consumption is evolving. It is quite likely that the huge energy efficiency gains achieved by technology evolution have at least been compensated by the surge in data traffic. Therefore, in this paper, we estimate the operational power consumption of cellular Base Stations (BSs) deployed in France from 2015 to 2022. However, unfortunately, the lack of openly available data hinders the estimation process. In order to work around this issue, we rely on a public dataset on radio electric installations, on widely adopted power consumption models and on a set of assumptions backed by the scientific literature. We demonstrate that, over the considered period, the numbers of BSs and transceivers have grown at a sustained Compound Annual Growth Rate (CAGR) of 7.55% and 18.27%, respectively. Within the same period, the average BS power consumption has increased at a CAGR of 9.89% while the total operational power consumption of BSs has grown at a CAGR of 18.18%. We further show that the introduction of `5G` has accelerated this trend despite the recent decommissioning of `2G` and `3G` transceivers. These alarming figures advocate for proactive digital sobriety policies.**

***Index Terms*—Mobile Network, 5G, Base Station, Power Consumption, Digital Sobriety, France.**

## I. INTRODUCTION

In recent years, the widespread proliferation of wireless mobile devices have prompted tremendous growth in the cellular communications industry [1]. Such industry expansions are carefully guided and encouraged by the mobile operators who continually strive to provide more capacity through their networks. This addition of capacity is not only to cater the increasing user demands but it is also an incentive for further traffic growth which eventually translates into higher profits. For this purpose, mobile operators deploy additional physical Base Stations (BSs) or reinforce the current ones. Several studies have investigated the Information and Communication Technology (ICT) sector's global climate impact. ICT represents between 1.8% and 3.9% of the global Green House Gas (GHG) emissions* [3]. Despite the huge energy efficiency gains achieved with the arrival of newer cellular generations of `4G` and `5G`, it is clear that these gains have at least been compensated by the increase in data traffic [4], [5]. Between 2002 and 2012, GHG emissions directly related to ICT, grew twice as fast as the overall global emissions. From 2012 till 2015, studies lead to contrasting conclusions [3]. However, all authors agree on the fact that this share will not significantly reduce if the business keeps running as usual. As mobile networks constitute a large part of the ICT sector, they are subject to ambitious targets of cutting down on GHG emissions, see e.g. the International Telecommunication Union (ITU) recommendation [6] which, by 2030, envisions a 45% reduction in the emissions of mobile network operators. But the rise in BS installations and deployments are a serious hindrance to this goal as BSs alone are responsible for approximately 80% of the total energy consumption of mobile networks [7], [8]. Due to such trends, the increased energy consumption of BSs has become a major issue which should gain more attention from the researchers.

The modern end-user devices with newer mobile generations like `5G` are becoming more and more energy-efficient in terms of energy per transmitted bit. However, these energy gains can easily be nullified due to the so called rebound effect [9], [10]. Direct rebound effect in mobile networks occurs when the changing consumer behaviour increases the usage of energy-efficient end-user devices to the point that the aggregate usage outweighs the potential energy savings. Hence, it is necessary to evaluate the total energy consumption in `J` or `Wh` to be able to quantify the overall impact and not only the energy efficiency in `J/bit`. However, historically, energy consumption at the BSs has been difficult to evaluate due to the lack of openly available data from the mobile operators and ICT equipment providers. On the other hand, users are expected to remain aware and conscious of their mobile usage in light of the growing environmental impact of mobile networks, especially if digital sobriety policies were to be implemented. This serious contradiction can partially be resolved with reliance on models and estimates which have their own share of advantages and drawbacks.

There exists a number of previous studies that try to estimate the aggregate energy consumption of mobile networks [11],

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[*] There is an inherent complexity in evaluating the carbon footprint of ICT due to, e.g., the lack of accurate data or the difficult definition of the sector's boundary, see [2] for a discussion. The range provided by [3] is rather pessimistic among literature's estimates.

[12], [13], [14]. The data used in these studies is mostly provided upon request by telecom network operators. Malmodin et al. investigate the electricity consumption and operational carbon emissions of telecom operators from 2010 to 2015 [11]. The same authors in [12], present the operational electricity consumption and GHG emissions for selected European telecom network operators from 2015 to 2018. A similar study is conducted for Finland where the current and future energy consumption trends for mobile networks are discussed [13]. Golard et al. present a method to evaluate and project the total energy consumption of radio access networks using on-site measurements provided by operators. This method is applied to come up with `4G` and `5G` BS models which are then used to predict the energy footprints for Belgium [14]. However, since most of these works use collective values from telecom operators, the break down of energy consumption is not quite clear and visible especially in terms of location, BSs, operators and mobile generations. Furthermore, the data collection methodology, calculation details and information about continuous historical data remain unknown.

Hence, this work attempts to estimate the national operational power consumption of cellular BSs in France between April 2015 and September 2022 using a public dataset on radioelectric installations, some specific power consumption models from the literature and accompanying assumptions related to the BS equipment. The key findings of this study are:

- The number of BSs has increased at a Compound Annual Growth Rate (CAGR) of 7.55% while the number of transceivers has grown at a CAGR of 18.27%. Furthermore, existing BS sites are reused for newer generations instead of dedicated BS deployments. In addition, since the introduction of `5G` in November 2020, the decommissioning of several `2G` and `3G` transceivers has compensated the inclusion of `5G` transceivers.
- Existing BSs are continually being reinforced with newer cellular technologies, leading to multi-generational BSs with an increased number of frequencies. Consequently, the average BS power consumption has increased at a CAGR of 9.89%.
- The total BS power consumption has increased at a CAGR of 18.18%. Since the introduction of `5G`, this increase has accelerated with a high CAGR of 19.75%. This highlights the existence of a direct rebound effect where the energy efficiency gains are negated due to the rise in BS deployments.
- We show that our estimates are coherent with other data sources, despite the uncertainty in the estimation process. This validates our approach.

We provide a brief description of the dataset and data processing in Section II. Section III presents the BS power consumption models. The numerical results are discussed in Section IV while Section V is for discussion. We conclude the paper in Section VI.

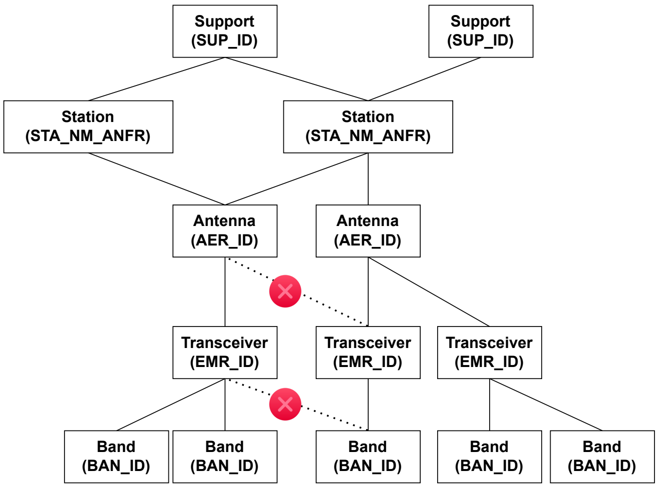


Fig. 1: Hierarchy in the ANFR dataset.

## II. ANFR DATASET AND DATA PROCESSING

### A. ANFR Dataset

This study is based on the public dataset on radioelectric installations above 5 W [15] from the Agence Nationale des FRéquences (ANFR) which is a governmental agency managing all radio frequencies in France (https://www.anfr.fr/en). The ANFR is tasked with the authorization of all transmission site deployments above 5 Watts in mainland France as well as in the overseas French territories. This publicly accessible dataset provides a unique opportunity for researchers to conduct studies on a national scale. The dataset contains data from all public and private operators of radio installations. It has been maintained from April 2015 and is updated on a monthly basis. Each of the data files can be considered as a table containing some specific information. The dataset gathers information about different elements of the radio installations, namely physical supports, BSs, antennas, transceivers and frequency bands.

There exists a hierarchy in the dataset that defines the relationship between these elements as depicted in Fig. 1. It can be seen that a support (also known as a site) is at the top of the hierarchy. Each support or site consists of several BSs which can belong to the same or different operators. In some rare cases, a single BS is attached to multiple supports. For example, when a BS uses two antennas that are more than 90 meters apart, then the BS is said to be supported by two different physical supports. A BS is owned by a single operator and utilizes one or more antennas. It is also possible that several BSs share the same antenna. This is due to the sharing of telecom infrastructure where competitors become partners to lower costs and investments. In France, leading mobile operators have signed mutual strategic agreements to share infrastructure among each other [16]. From the dataset, we observe that as of September 2022, around 17.86% of the antennas are shared between BSs belonging to several different operators. An antenna is associated with one or more transceivers. However, one transceiver can only use a single antenna. Lastly, a transceiver can operate multiple frequency bands but those bands belong to only a single type of wireless communications standard/technology.

### *B. Data Processing*

We use python as the programming language for dataset processing. Specifically, python's Pandas library is mainly employed because of its support for cleaning, manipulating and analyzing tabular data.

First, we preprocess the dataset before performing the analysis and computations related to power consumption. This is to filter out irrelevant information from it and reduce the data size. For this preprocessing stage, we only consider the cellular technologies/standards. These include `GSM 900`, `GSM 1800`, `GSM 900/1800`, `UMTS 900`, `UMTS 2100`, `UMTS 2100/900`, `LTE 700`, `LTE 800`, `LTE 1800`, `LTE 2100`, `LTE 2600`, `NR 700`, `NR 2100` and `NR 3500`. Overall, all the mobile communication generations are taken into account while excluding their experimental bands such as `LTE 1400 Expe`. Furthermore, we only consider the four leading French operators as they hold the majority of the market share and hence, their data samples are representative of the entire dataset. In addition, only the *in service* BSs are taken into consideration, *i.e.*, authorized BSs not yet *in service* are excluded from the analysis. We then utilize the compact preprocessed dataset for faster data analysis and power consumption related calculations. The complete source code of the project with further details on the dataset and data processing is publicly available on GitHub [17].

## III. BS POWER CONSUMPTION MODELLING

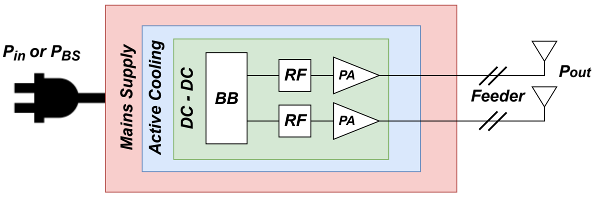
We rely on accepted models from the literature for performing our power consumption estimations.

### *A. Power Consumption Models*

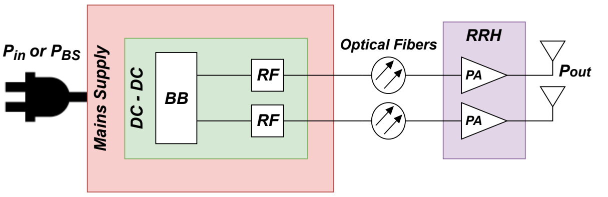
*1) EARTH Model:* The Energy Aware Radio and Network Technologies *(EARTH)* project defines a widely used BS power consumption model [18]. The EARTH model assumes that all BSs can be generalized such that they consist of multiple transceivers where each transceiver serves a single antenna element. Each transceiver chain includes a power amplifier (PA), a RF small-signal transceiver module, baseband boards (BB), a DC-DC power supply, an active cooling system and an AC-DC unit (mains supply) for connection to the electrical power grid [18]. The mathematical formulation of this model is the following:

$$P_{BS} = N_{TRX} \times \frac{P_{PA} + P_{RF} + P_{BB}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \tag{1}$$

where $P_{BS}$ is the total BS power consumption, $P_{PA}$ is the PA power consumption, $P_{RF}$ is the power consumption of the transceiver module and $P_{BB}$ is the baseband power consumption. In addition the $\sigma_{DC}$, $\sigma_{MS}$ and $\sigma_{cool}$ are the power losses in the DC-DC power supply, mains supply and active cooling system, respectively. Furthermore, $N_{TRX}$ is the number of transceiver chains present in the BS. The power consumption of the PA is calculated as follows:



(a) *Integrated BS Model.*



(b) *RRH based BS Model.*

Fig. 2: Two types of BS models along with their sub-units.

$$P_{PA} = \frac{P_{out}}{\eta_{PA} \times (1-\sigma_{feed})} \tag{2}$$

where $P_{out}$ is the output RF transmit power, $\eta_{PA}$ is the power efficiency of the PA and $\sigma_{feed}$ is the feeder/cable loss arising due to the physical distance between the BS and the antenna. Note that $P_{out}$ is generally an increasing function of the cell load and of the signal bandwidth.

We consider two types of BS models namely, the integrated BS model and the Remote Radio Head (RRH) based BS model [19]. These models are shown in Fig. 2. An integrated BS exists as a single unit placed at a distance from the antennas. The PAs require active cooling within the BS and are connected to the antennas via long feeder cables. This results in power losses of $\sigma_{cool}$ and $\sigma_{feed}$ which are already taken into account by Equation 1. On the other hand, in RRH based BSs, a RRH is introduced for hosting the PAs at the same physical location as that of the antennas. The RRH is connected to the BS using optical fibers while the antennas are connected to the RRH through small flexible jumpers. As a consequence, the feeder loss is reduced to a lower value. The cooling loss is completely avoided as the PAs inside the RRH are now cooled through natural air circulation.

*2) `5G NR 3500` specific Model:* The EARTH model is applicable to a wide range of BS types. However, it does not accurately model `5G` BSs operating at the 3500 MHz band. This is because at this frequency, Massive MIMO is employed which requires the presence of several active antenna elements inside an Active Antenna Unit (AAU). Hence, we select a specific power consumption model that models `5G` BSs considering the impact of this massive beam-forming functionality [20]. This model estimates the total BS power consumption as follows:

$$P_{BS} = N_{TRX} \times \left( \frac{P_{out}}{\eta_{PA}} + N_{TXRU} P_C + P_{Base} \right) \quad (3)$$

where $P_{out}$ is the output RF transmit power of the AAU, $\eta_{PA}$ is the power efficiency of the PA, $N_{TXRU}$ is the number of transceiver units inside the AAU, $P_C$ represents the additional digital and RF processing needed for each antenna branch and $P_{Base}$ is the baseline power consumption. Furthermore, $N_{TRX}$ corresponds to the number of complete transceiver chains utilizing a single AAU present in the BS. In practice, $N_{TRX}$ is equal to the number of sectors at the BS (typically 3).

It is to be noted that only a few models take Massive MIMO into account. Another one is described in [21]. However, numerical values of [20] provide better estimates when compared to publicly available data, like in [22].

*3) Dependence on Load:* The output power $P_{out}$ is an increasing linear function of the load, i.e., the average proportion of radio resources used for the transmission. Assuming that the BS has a maximum transmit power $P_{max}$, we compute the output power as follows: $P_{out} = \rho \times P_{max}$, where $\rho$ is the BS load. This linear model is sufficiently accurate to be well accepted by the literature, see e.g. [18], [23], [21].

### B. Performance Improvements

The variable values in equations (1), (2) and (3) do not remain fixed but are updated with time in order to take into account the continuous technological improvements resulting in increased BS power efficiencies. In general, the analog RF circuitry and the digital baseband circuitry are subject to technology scaling on the basis of Moore's law [24]. Moreover, a reduction of 2% per year is observed in the power lost inside a PA [24]. Therefore, the values of $P_{RF}$, $P_{BB}$ and $\eta_{PA}$ are updated as follows:

$$P_{RF}^{n} = \frac{P_{RF}}{L_{P_{RF}}^{\lfloor \frac{n}{2} \rfloor}} \quad (4)$$

$$P_{BB}^{n} = \frac{P_{BB}}{L_{P_{BB}}^{\lfloor \frac{n}{2} \rfloor}} \quad (5)$$

$$\eta_{PA}^{n} = \eta_{PA} \times L_{\eta_{PA}}^{n} \quad (6)$$

where $P_{RF}^n$ is $P_{RF}$ at year $n$, $P_{RF}$ is at year 0 and $L_{P_{RF}}$ is the constant scaling factor for $P_{RF}$. Similarly, $P_{BB}^n$ is $P_{BB}$ at year $n$, $P_{BB}$ is at year 0 and $L_{P_{BB}}$ is the constant scaling factor for $P_{BB}$. Lastly, $\eta_{PA}^n$ is $\eta_{PA}$ at year $n$, $\eta_{PA}$ is at year 0 and $L_{\eta_{PA}}$ is the constant per year scaling factor for $\eta_{PA}$. In (4) and (5), $\frac{n}{2}$ is subject to integer division since Moore's law is applied every two years.

Equations (4), (5) and (6) are applied for state-of-the-art BSs at year $n$. We assume that, according to the dataset, when a new BS is put *in service* at year $n$, such a state-of-the-art equipment is installed. This particular BS will keep the same parameters until year $n + d_{LT}$, where $d_{LT}$ is the average BS lifetime duration in years. At year $n + d_{LT}$, the values of $P_{RF}$, $P_{BB}$ and $\eta_{PA}$ are updated to $P_{RF}^{n+d_{LT}}$, $P_{BB}^{n+d_{LT}}$ and $\eta_{PA}^{n+d_{LT}}$ respectively, as if a current state-of-the-art BS were deployed.

TABLE I: Assumption set for the EARTH model.

| | **Integrated BS** | **RRH based BS** |
|---|---|---|
| Tech. | `2G`, `3G` and `2G/3G` | `4G`, `5G`, `3G/4G`, `4G/5G`, `2G/4G`, `2G/5G`, `3G/5G`, `2G/3G/4G`, `3G/4G/5G`, `2G/4G/5G`, `2G/3G/5G` and `2G/3G/4G/5G` |
| MIMO | Single transmitter | For `4G` and `5G` transceivers only.<br>• `2T2R` MIMO for lower bands including `LTE 700`, `LTE 800` and `NR 700`.<br>• `4T4R` MIMO for higher bands including `LTE 1800`, `LTE 2100`, `LTE 2600` and `NR 2100`. |
| $\sigma_{feed}$ | 0.5 | 0.2 |
| $\sigma_{cool}$ | 0.1 | 0 |
| $\sigma_{DC}$ | 0.075 | |
| $\sigma_{MS}$ | 0.09 | |
| $P_{RF}$ | 12.9 W | |
| $P_{BB}$ | 29.6 W | |
| $\eta_{PA}$ | 0.311 | |
| $P_{max}$ | 4 W per downlink MHz. | |
| $L_{P_{RF}}$ | $\sqrt{2}$ | |
| $L_{P_{BB}}$ | 2 | |
| $L_{\eta_{PA}}$ | 1.02 | |
| $d_{LT}$ | 8 years | |
| $\rho$ | 0.3 | |

Note that we apply these performance improvements to the EARTH model only and not to the `5G NR 3500` specific model. This is because the `5G NR` is a relatively new technology and its models do not yet require time based scaling.

## IV. NUMERICAL RESULTS

### A. Numerical Assumptions

In order to obtain the variable values of the BS consumption models, we make appropriate assumptions since the information regarding BS equipment is proprietary and kept confidential by the operators as well as the equipment manufacturers.

The information coming directly from the preprocessed dataset includes $N_{TRX}$ that is the number of complete transceiver chains in each BS, total bandwidth associated with each transceiver, the duplex mode of each transceiver and the year in which each BS becomes *in service*. In order to get the value of $N_{TRX}$ at a BS, we group together and count all transceivers with the same characteristics. In addition, we calculate the total bandwidth of each transceiver by using the starting and ending frequency fields provided in the dataset. Furthermore, for determining the duplex mode, we observe their associated frequency bands and the related regulation. Lastly, for each BS, a date of service field is provided in the dataset which we use for getting the *in service* date.

Tab. I presents all the assumed values for each transceiver signal chain for power consumption related calculations with the EARTH model. We use the values *measured* (in 2011) and not *estimated* (for 2020) by the EARTH model but then apply the improvement procedure as described in Section III-B. The improvement figures for $L_{P_{RF}}$, $L_{P_{BB}}$ and $L_{\eta_{PA}}$ are taken from [24]. From Tab. I, it can be seen that the BSs are

TABLE II: Assumption set for the `5G NR 3500` model.

| MIMO | `64T64R` MIMO with the use of an AAU. |
|---|---|
| $P_{Base}$ | 260 W |
| $\eta_{PA}$ | 0.25 |
| $P_{max}$ | 240 W |
| $N_{TXRU}$ | 64 |
| $P_C$ | 1 W |
| $\rho$ | 0.3 |

classified as either integrated or RRH based BSs. This is determined based on the general industry practice where BSs belonging to the recent cellular generations of `4G` and `5G` are using RRHs. Similarly, the Multiple-Input Multiple-Output (MIMO) configurations are also assumed. Mainly, the lower bands of `4G` and `5G` employ `2T2R` MIMO while the higher bands up to 2.6 GHz use `4T4R` MIMO. Furthermore, the values for $\sigma_{feed}$, $\sigma_{cool}$, $\sigma_{DC}$, $\sigma_{MS}$, $P_{RF}$, $P_{BB}$ and $\eta_{PA}$ are adopted from the original work of the EARTH model [18]. Specifically, the value of $\sigma_{feed}$ is reduced from 0.5 to 0.2 for RRH based BSs in comparison with integrated BSs. This is because the general feeder loss value for integrated BSs is 3 dB while for RRH based BSs is 1 dB [25]. In addition, the maximum output power $P_{max}$ depends on the bandwidth of the transceiver. We follow here the simple 4 W/MHz rule as in [14], where the considered bandwidth is only for downlink. For Frequency Division Duplexing (FDD), this is exactly the transceiver bandwidth. For Time Division Duplexing (TDD), the considered bandwidth is 2/3 of the transceiver bandwidth. We assume the average BS lifetime duration to be 8 years after which it is replaced with up-to-date equipment. This value is based on the fact that the lifetime of a typical BS is between 5 to 10 years [26]. We also assume a realistic load of $\rho = 30\%$ which is close to the average load in busy hours [14].

Tab. II presents all the assumed values for the `5G NR 3500` specific model. The values in Tab. II are largely taken from [20]. The $P_{max}$ is now significantly higher at a value of 240 W as compared to the EARTH model due to the presence of a `5G NR 3500` AAU in the signal chain [22].

### B. Equipment Count

In this section, we discuss the insights extracted from the preprocessed dataset. These insights do not depend upon the selected power consumption models nor on our assumptions.

Fig. 3 shows the total count of *in service* BSs with respect to the cellular technology in France from 2015 to 2022. From the most recent data point, it is revealed that there are over 100,000 *in service* cellular BSs in the country. Furthermore, it is observed that the majority of the BSs support multiple cellular generations. Since `2G` and `3G` mobile networks are gradually becoming obsolete, a sharp downward trend is observed in the numbers of only `2G`, only `3G` and `2G/3G` BSs. On the contrary, during the same time period, BSs of the type `2G/3G/4G` and `3G/4G` have been increasing due to the addition of `4G LTE` transceivers to the BS sites. Furthermore, with the authorization and commissioning of `5G` transceivers in November 2020 as indicated by the vertical line, `2G/3G/4G/5G` and `3G/4G/5G` BSs have started to appear which are now quickly increasing in number. We determine that between April 2015 and September 2022, the number of BSs has grown at a sustained CAGR of 7.55%. Even if only the period after the introduction of `5G` BSs is considered, the CAGR value does not deviate much and is 7.2%. From this, we deduce that the newer generations reuse existing infrastructure instead of dedicated BS deployments. Hence, BSs are now supporting an increased number of cellular standards and frequency bands. This trend is also exemplified by the fact that in 2020, 97% of the `5G` towers in China were constructed on existing sites [27].

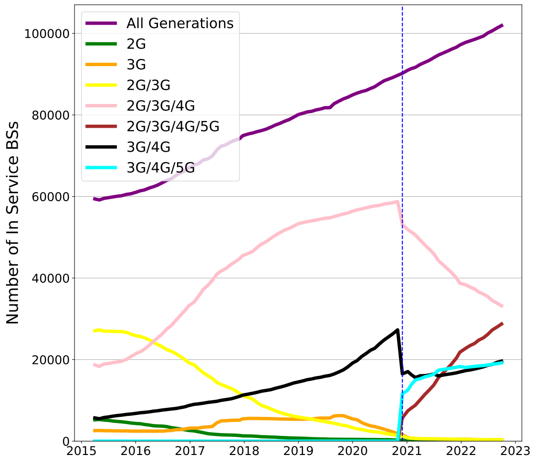


Fig. 3: Number of *in service* BSs by technology in France (the vertical line indicates the introduction of 5G in France).

Fig. 4 presents the number of transceivers by cellular technology. Currently, the total number of transceivers exceeds more than 1,600,000. As expected, we observe that the growth of `2G` and `3G` transceivers has stagnated in the recent past whereas `4G` and `5G` transceivers have been rising. A CAGR of 18.27% is calculated for transceivers from April 2015 to September 2022. Since the introduction of `5G`, the transceivers' CAGR for only the next 12 months is found to be 21.65%. However, when we consider the complete duration since the introduction of `5G`, the CAGR drops to 17.09%. This is due to the increase in decommissioning of several `2G` and `3G` transceivers in 2022.

### C. Operational Power Consumption

Fig. 5 depicts the calculated total BS operational power consumption according to the cellular technology. As BSs generally include several generations of the technology, we only represent the most significant combinations. It can be seen that there is an almost 3.5-fold increase in the aggregate BS power consumption over the span of 7 years. Currently, the total BS power consumption crosses 350 MW which translates into 3 TWh energy consumption per year (approximately 0.7% of the total electricity consumption in 2021 in France [28]). Since the introduction of `5G` transceivers with high power

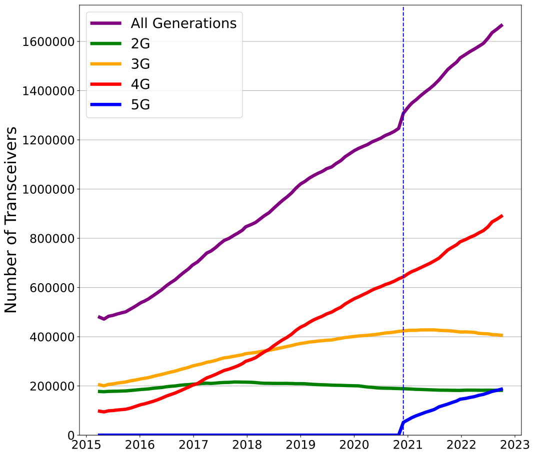


Fig. 4: Number of transceivers by technology in France.

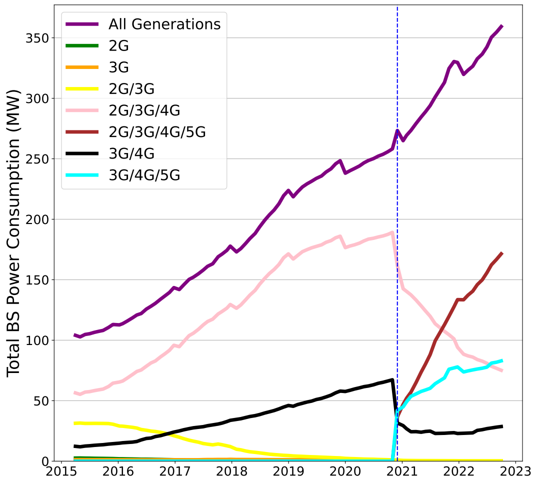


Fig. 5: Total BS power consumption in France.

demand at the end of 2020, there has been a slight acceleration in energy consumption. We compute that between April 2015 and September 2022, the total BS power consumption has increased at a sustained CAGR of 18.18%. Moreover, since the introduction of `5G` BSs, we found the power consumption to have grown at a higher CAGR of 19.75%. This exhibits the presence of a direct rebound effect where increasing BS installations nullify the energy efficiency gains attributed with newer cellular generations such as `5G`.

We also observe that, from April 2015 to September 2022, the average BS power consumption went from 1.75 kW to 3.53 kW. This translates into a sustained CAGR of 9.89%. Considering only the period after the introduction `5G`, the average BS power consumption CAGR has escalated to 11.7%. This is caused by the continuous reinforcement of current BSs with new cellular technologies. Fig. 6 demonstrates how the average BS power consumption rises with the number of supported frequency systems as of September 2022. As expected, the lower the number of frequency systems, the lower is the average power consumption at the BS.

Fig. 7 shows the average BS power consumption with respect to the highest technology present at the BS as of September 2022. Here, a highest BS technology type includes all systems before it. For example, `3G` BSs include `2G`, `3G` and `2G/3G` BSs. We make a distinction between the lower bands and the `3500 MHz` band of `5G` in order to clearly demonstrate the effect of using `5G` AAUs on the average BS power consumption. The general trend is that the average BS power consumption rises with the existence of higher cellular generations at the BS. Specifically, BSs with the `5G 3500 MHz` transceivers consume the highest power due to the presence of Massive MIMO supporting AAUs.

## V. Discussion

In this section, we check the coherence of our results with other sources and perform a sensitivity analysis related to some model parameters.

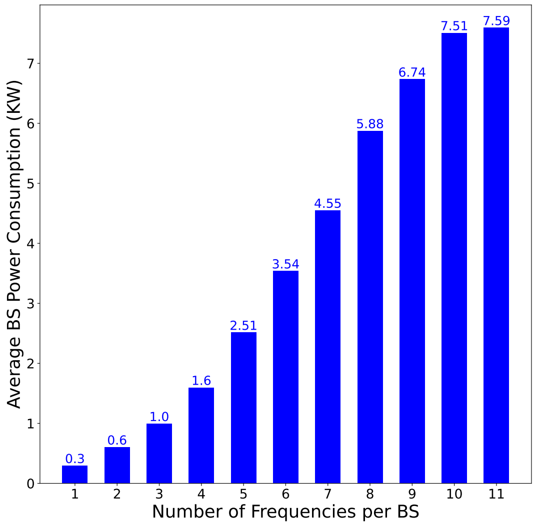


Fig. 6: Average BS power consumption at 30% by the number of frequencies (France, Sept. 2022).

### A. Coherence with other sources

Since we don't have access to private data of the operators, it is difficult to verify the accuracy of the obtained results over the years. We thus crosscheck our estimates with other sources of data. Lundén et al. present the operational electricity consumption for European telecom network operators between 2015 to 2018 [12]. In this study, values for mobile access networks are provided for a number of mobile subscriptions ranging between 255 millions to 265 millions. In the same period, the number of mobile subscriptions in France went from 66.68 million to 70.42 million [29]. We thus scale down (French subscriptions represent 26%) the values of [12] and provide the comparison in Tab. III. From the second column of the table, it can be seen that our estimate accounts for 40% to 70% of Lundén et al. evaluation. The difference can be explained by the scope of [12] which includes the whole mobile network while we are focusing on BSs. BSs are indeed

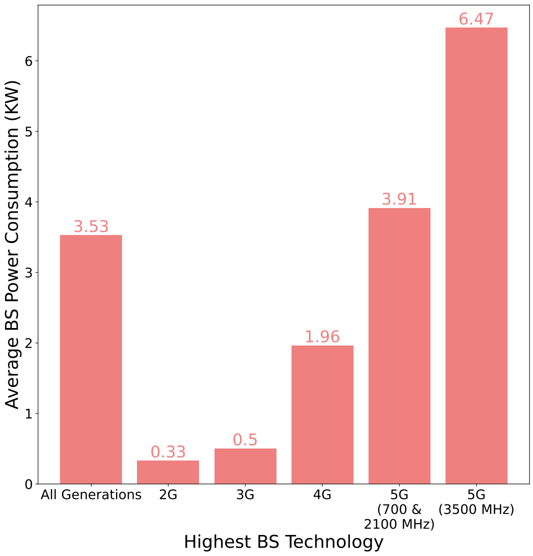


Fig. 7: Average BS power consumption at 30% load by highest BS technology (France, Sept. 2022).

TABLE III: Comparison with Lundén et al.'s average annual power consumption (2015-2018) [12].

| Year | Lundén et al. scaled (whole mobile network) [MW] | Lundén et al. scaled×80% [MW] | Our Work (BSs) [MW] |
|---|---|---|---|
| **2015** | 261 | 208 | 107 |
| **2016** | 267 | 213 | 126 |
| **2017** | 273 | 218 | 160 |
| **2018** | 282 | 225 | 197 |

known to represent approximately 80% of the consumption of mobile networks [7]. If we apply this factor to the scaled values, we obtain the third column of the table. With these rough approximations, our approach provides values at 48% and 41% from the estimation in 2015 and 2016, respectively, but at only 26% and 12% in 2017 and 2018. Note that the linear scaling of the European values to just France, ignores the country-wise dynamics that define this contribution to the total consumption

Another important source of comparison is a recent report from the French telecom regulator ARCEP on the data collected in 2020 [30], see Tab. IV. This data is related to both fixed and mobile networks of the operators (all equipment in the access, back-haul and core networks). If we apply a "rule of thumb" of 60% for the mobile networks [31] and 80% for the BSs [7], we obtain the third column of the table. Again, we obtain the same order of magnitude without relying on proprietary data: differences of 29%, 6%, 6%, 16% and 17% can be observed from 2016 to 2020.

In [31], it is mentioned that the French mobile operator "Free" consumed 456 GWh of electricity in 2017, out of which 60% was for its mobile network. Taking into account a 80% share only for BSs [7], leads to an installed power of 24 MW in 2017. By filtering the BSs deployed by "Free" in the dataset, we are able to estimate an average power consumption of 26.6 MW in 2017. This shows that our estimate is very close to the reported value.

TABLE IV: Comparison with ARCEP collected data (2016-2020) [30].

| Year | ARCEP (fixed and mobile networks) [MW] | ARCEP×60%×80% [MW] | Our Work (BSs) [MW] |
|---|---|---|---|
| **2016** | 340 | 163 | 126 |
| **2017** | 353 | 169 | 160 |
| **2018** | 387 | 186 | 197 |
| **2019** | 408 | 196 | 234 |
| **2020** | 434 | 208 | 250 |

According to [27], a 64T64R three-sectorized 5G macro BS consumes approximately $3-4$ kW which is 2 to 3 times higher than 4G equipment. The factor of 3 between 4G and 5G BSs is also given by an Executive Vice-President of China Mobile in [32]. The president of EJL Wireless Research mentioned in [32] that a typical 5G site consumes 10 kW. The ITU-T Recommendation [33] reports a typical consumption of 8 kW for a 2G/3G/4G/5G BS. In [22], a 64T64R 5G NR BS with transmit power of 240 W operating on 100 MHz bandwidth is said to consume 4297 W of power (about four times the consumption of a 8T8R 4G BS with 40 W on 20 MHz). These sources do not precise the corresponding load values. Based on our results shown in Fig. 7, the average power consumption of a 4G (highest technology) BS is 1.96 kW. Furthermore, on average, BSs equipped with only the lower bands of 5G consume 3.91 kW while BSs running the 3500 MHz band consume 6.47 kW at 30% load. Our results verify that 5G BSs consume 2 to 3 times more power than 4G BSs. In addition, for 64T64R 5G BSs, our value of average power consumption lies between the reported values of $4.23 - 10$ kW.

## *B. Sensitivity analysis*

Given the nature of our employed methodology to calculate power consumption, it is possible that small changes in some model parameters may cause a large deviation in the final results. Hence, we present here a brief sensitivity analysis by varying two parameters one by one. It is to be noted that except for the varied parameter, all other values are the same as before. Fig. 8 depicts the total BS power consumption in France at loads varying from 10% to 40% with a step of 5%. Similarly, Fig. 9 shows the total BS power consumption curve at several different average BS lifetime (LT) duration. These curves suggest that the assumption on the average BS lifetime duration does not significantly impact the results. On the contrary, the average load has a determining influence on the computed total power consumption. This means that more accurate load estimations, taking into account the space and time dynamics, are required to continue the work presented in this paper.

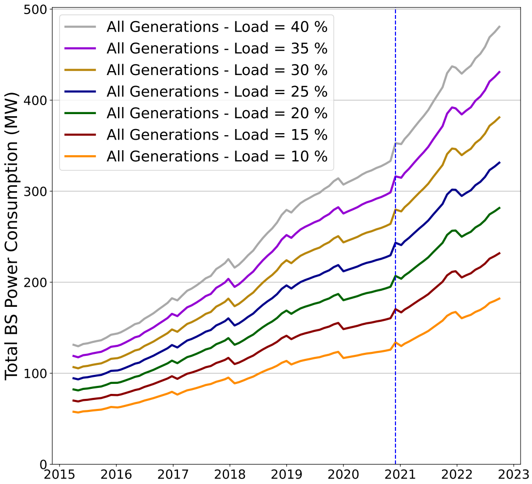


Fig. 8: Total BS power consumption with varying the average load ($\rho$) in France.

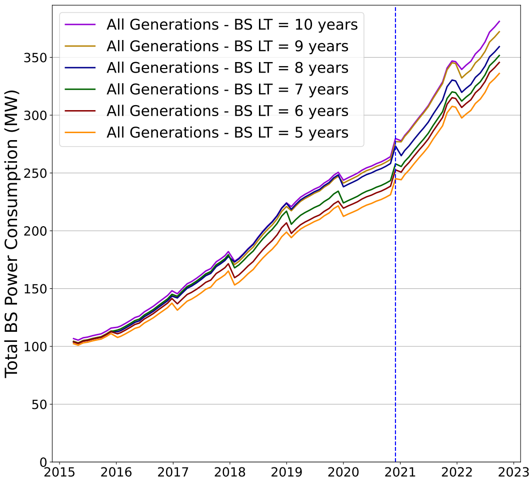


Fig. 9: Total BS power consumption with varying the average BS lifetime (LT) duration in France.

## VI. CONCLUSION

In this paper, we propose an estimation of the operational power consumption of cellular BSs in France from 2015 to 2022. We base our methodology on a public dataset on radioelectric installations, widely adopted BS power consumption models and realistic assumptions from the literature. We highlight the fact that the number of BSs, the number of transceivers, the average BS power consumption and the national power consumption are growing at sustained CAGRs of 7.55%, 18.27%, 9.89% and 18.18% respectively. So far, the introduction of `5G` has not significantly modified the rate of increase in the numbers of BSs and transceivers thanks to the practice of co-siting and the decommissioning of `2G/3G` transceivers, respectively. However, it has caused an acceleration in growth rates of the average and the national BS power consumption. Without access to proprietary data, it is difficult to check the accuracy of our results. However, the comparisons with recent publications show that we obtain the right order of magnitude. Certainly, our estimates are intended to be preliminary in nature with the major goal of starting a discourse around the topic. These estimates can be further refined in the future to make them more accurate. For example, the space and time heterogeneity of the traffic could be taken into account in place of an average load per BS, or a model for sleep modes in `5G` could be introduced. However, if our estimates are confirmed, the alarming figures we show here would call for proactive digital sobriety policies.

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