How to favour more cooperative deployments for Network Infrastructures

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***Abstract*—Many mobile network operators have committed to become net zero carbon. To succeed, they need to activate many levers, upon which sharing network infrastructures appears as inevitable. In this paper, we highlight some current implementations of network infrastructures sharing. We then compare two different scenarios: a business-as-usual scenario, corresponding to the current situation in France, and a fully cooperative and ideal scenario. Opportunistically using the available data, we draw a model to estimate carbon savings between these two scenarios. This model estimates that carbon savings thanks to radio access network sharing would go up to 79% in France. Indeed, the current French regulation framework, which includes coverage and performance requirements, leads to overlapping networks and high overdimensioning. The savings highlighted in this paper embed the consequences of both.**

Conversely, the fully cooperative and ideal scenario assumes a change in the regulatory framework, in which network infrastructures as rather considered as a common good. To favor the emergence of such framework reducing environmental impacts by design, a new indicator, the Sufficiency Deployment Index (SDI), is specified. It measures the sufficiency of multi-operator network infrastructure deployments on a given territory.

Future work shall enhance the model, by embracing the consequences of infrastructure sharing, using a consequential approach. Moreover, new business models will have to emerge, created on the economic, social and societal values for all actors of the ecosystem. A single actor cannot change its business model alone.

***Index Terms*—sustainability, assessment, GHG, carbon footprint, Radio Access Network, 5G, sharing, environmental transition, digital transition**

I. Introduction

The ongoing environmental transition focuses firstly on climate constraints [1], gradually breaking them down into a two-dimensional financial and carbon accounting. Yet reducing carbon emissions should not transfer impacts to other planetary limits, including abiotic resources and biodiversity [2]. In particular, critical minerals represent another huge challenge to keep in mind while finding a path to a net zero future. They also represent a geopolitical challenge, as illustrates China's decision to stop any export of Germanium and Gallium since July 2023 [3]. Moreover, the mining of these critical minerals is a threat to biodiversity, a major source of pollution, and therefore a major environmental issue [4].

A. The digital sector's environmental impact is increasing

In the meantime, the digital transition is leading humanity to an always-on future. This is causing the digital world to spread far beyond its traditional borders, and in particular far beyond Information and Communication Technology (ICT). As a consequence, assessing the environmental impact of the digital world becomes tricky [5]. The Shift Project estimates the carbon impact of the digital sector, which currently would represent less than 4% of humanity's carbon impact, could grow at a tremendous rate of 6% per year [6], [7].

This article focuses on mobile network operators' (MNO) common need to operate networks that provide iso-services, transparent to end-users, yet consuming less resources and emitting less carbon. Because it allows network operators to do just as well with less resources, sharing network infrastructures is already seen as a powerful lever, consistent with these numerous and systemic challenges [8]. This powerful lever is probably inevitable on the path towards a net zero attractive future, offering multiple climatic, economic, geopolitical, and environmental benefits.

B. How networks contribute to the digital sector's impact

This article concentrates on telecommunication networks, which are part of the ICT sector. Within the ICT sector, networks account for 5% of the environmental impact [7] (figure 5 p. 13), [9]. According to GreenIT [10], networks generate 22% of ICT's Greenhouse Gas (GHG) emissions and use 17% to 23% of ICT's energy consumption [11]. Within the network domain, Radio Access Networks (RAN) use approximately 80% of the energy consumption [12]. This is why the French regulation agency, the ARCEP, has assessed the energy consumption of 4G and 5G network deployments [13]. Our objective in this article is to focus on mobile networks' carbon footprint. As a prerequisite, note all GHG emissions are calculated separately and then converted to

CO_2e[1]. Thus, by misuse of language, GHG assessment is referred to here as the carbon assessment.

Today operators are strongly competing for deploying the best-in-class RAN infrastructures, offering the highest throughput, the lowest latency and the widest coverage. Another motivation is that 5G networks are expected to be more energy efficient than 4G networks, for the same amount of transmitted data [13], [14]. Yet 5G networks need to be sufficiently loaded to meet this promise.

As illustrated in Ivory Coast [15] where the government forces cooperation for more efficient 5G deployments, other models are possible. Senegal is another interesting illustration, with the national authority urging mobile operators to cooperate through national roaming to reduce network coverage gaps [16].

To our knowledge, the environmental impact of deployed 5G networks has not been studied yet. In that perspective, all consequences of 5G network deployments should be identified and assessed. In particular, the number of kilometers travelled for operational needs, including maintenance and repair should be assessed, and so should the impact on the change of smartphone.

Even if it may appear contradictory with the ongoing competition, many network operators have committed to be net zero carbon no later than 2040, including for instance Vodafone [17], BT [18], [19], Telefonica [20], [21], Deutsche Telekom [22], Telenor [23], KPN [24], TIM [25], MTN [26]–[28] and Orange [29], while Telia targets 2030 [30].

To reach that ambition, the first step is to analyze and model the company's current carbon footprint [29]. It embeds all GHG emissions, and is the sum of scopes 1, 2 and 3, as specified by the GHG Protocol [31]. Many companies already analyse their carbon footprint, as this is mandatory in more than 40 countries worldwide for large companies [32]. Scope 1 refers to direct GHG emissions, occurring from sources owned or controlled by the company, for example by heating the company's buildings or fueling company's vehicles. Scope 2 refers to purchased energy indirect GHG emissions, including GHG emissions induced by the electricity consumed by the company. This scope highly depends on the local energy mix. Scope 3 refers to other indirect GHG emissions and are a consequence of the activities of the company, although they occur from sources not owned or controlled by the company [33]. It includes the extraction and production of purchased equipment or transportation of purchased fuels, and use of provided services or devices. Scope 3 is often the one weighing the most in terms of GHG emissions.

Network infrastructure sharing is expected to significantly reduce mobile operators' scope 2 (energy consumption) and scope 3.

[1]A carbon dioxide equivalent or CO2 equivalent (abbreviated as CO_2e) is a metric measure used to compare the emissions from various GHG on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide (CO_2) with the same global warming potential.

C. Explore disruptive scenarios

This article assesses the carbon savings of a RAN infrastructure deployed on a given territory, compared to an ideal and fully shared RAN infrastructure. The results are computed only in France for practical reasons, because it requires having access to key databases. They could be computed for any region or country covered with several overlapping cellular networks, provided we had access to the required data.

To build the reference scenario, the study assumes MNOs are no more competing for coverage and performance. In other words, regulation and economic contexts have evolved, allowing all MNOs to freely share all their RAN infrastructure components and frequencies. Thus RAN resources are more considered as a common good than as a differentiating factor in our fully cooperative and ideal scenario. However this raises a key question: how could telecommunication companies differentiate if they were to rely on the same infrastructure?

Even if the Business Model is still to be found, the environmental benefits are clear. In particular, this article addresses how far sharing network infrastructures could reduce the overall carbon footprint of mobile operators. As we will see in the next section 2, our model estimates that savings would go as far as 79% in France, where 4 operators are competing.

Nevertheless, the emergence of new sustainable post-5G network infrastructure deployments is a huge challenge. We believe economic actors can hardly act alone. They need new sustainable regulatory frameworks to move on. This article thus suggests a novel Sufficiency Deployment Index (SDI) which allows comparing several deployment scenarios. This Sufficiency Deployment Index could be used to enlighten the debate between operators and regulators. Hopefully, a new regulation schemes will emerge from this debate.

D. Paper organization

Section II provides a glimpse at several RAN sharing operational deployments. Section III provides a rough and optimistic estimation of savings that could be possible thanks to RAN sharing. Section IV provides a Sufficiency Deployment Index, to compare several deployment scenarios.

II. A GLIMPSE AT RAN SHARING INITIATIVES

Before modeling the carbon savings induced by RAN sharing, this section provides an overview of the possible RAN sharing implementations.

The concept of sharing RAN resources has rapidly grown these last years [34] as shown in the Figure 1. It depicts sharing from a basic site sharing to Multi-Operator Core Network (MOCN) and to Multi-Operator Radio Access Network (MORAN), without forgetting roaming. Shared RAN resources are firstly achieved through MOCN and MORAN.

In RAN passive site sharing, the same passive infrastructure (tower) is used by all operators. Each operator uses its own backhaul network, antennas and frequencies. In RAN passive backhaul sharing, the same passive infrastructure (tower and backhaul) is used by all operators. Each operator uses its own antennas and frequencies. It is already operational on more

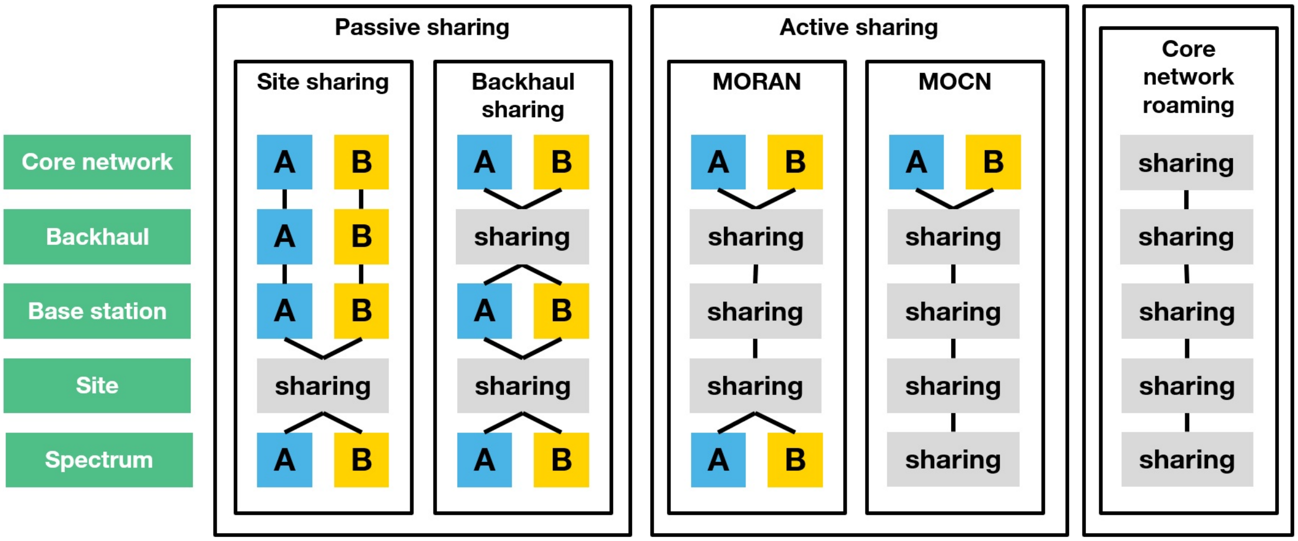

Fig. 1. Passive and active RAN sharing options

than half of the radio sites on the French territory. In this case, the technical environment is most often common to all operators, including power supply, pylons and civil engineering. It thus already significantly reduces the environmental impact of RAN infrastructures.

In the MORAN active sharing, the same passive infrastructure (tower and backhaul) is used by all operators. Operators share their antennas but use separate frequencies. As we will see in the section III-B, currently 12,02% of the antennas deployed on the French territory are shared between 2 operators, using MORAN active sharing.

In the MOCN active sharing, operators share their antennas. Frequency bandwidths can be provided by one of the operators or alternatively shared by all operators.

In the core network roaming, one operator shares its antennas and frequencies with other operators. This model is widely used, for instance in case of international roaming. When a client of a Home MNO H travels abroad, international roaming allows him to attach to a visited MNO V. Like in all network infrastructure sharing options, the two operators must have previously signed a one-to-one contract.

Moreover, network infrastructure sharing may be an opportunity in specific areas or countries. For instance, when travelling with the Paris underground network, end-users attach to the network through a MORAN. In this case network resources are deployed by Totem, a tower company and Orange subsidiary [35].

Today network management is mostly manual, making it difficult to integrate physical network equipment into a network service without a common network operation center. Similarly, when a network function is configured by a third party, it is difficult to ensure that the configuration will perform according to the negotiated contract. In many shared networks such as MOCN and MORAN [36], a joint venture is created with dedicated staff responsible for the daily operation of the various networks [37]. This is possible only for long-term contracts (e.g. 10 years).

In the future, the network will be dynamic and available on-demand through end-to-end service orchestration and automation. Network programmability will be possible through interfaces allowing, for example, service orchestration based on end-to-end connectivity service life-cycles across one or more network service domains from different providers [38]. This dynamicity is expected to facilitate and extend the implementation of network infrastructure sharing, having the potential to reduce the burden of one-to-one contracts.

Many acronyms and notations being used in this paper, the following list shall make reading easier.

- 2G, 3G, 4G, 5G: 2^{nd}, respectively 3^{rd}, 4^{th}, 5^{th}, generation cellular network
- AMTI: Annual Mobile Traffic Increase
- ANFR: French national frequency agency
- ARCEP: French regulation agency
- CO_2e: measure of all greenhouse gases
- GHG: GreenHouse Gas
- ICT: Information and Communication Technology
- ITU-T: International Telecommunication Union - Telecommunication standardization sector
- MNO: Mobile Network Operator
- MOCN: Multi-Operator Core Network
- MORAN: Multi-Operator Radio Access Network
- PRB: Physical Resource Blocks
- QoS: Quality of Service
- RAN: Radio Access Networks
- SDI: Sufficiency Deployment Index
- Totem: Tower company and Orange subsidiary

III. Estimating the decarbonation potential of RAN sharing

For sketching MNOs' net zero trajectory, the decarbonation potential of several levers needs to be estimated.

This section explores dynamic RAN sharing, assuming the regulation allowed all MNOs to share all their RAN infrastructure components and frequencies. Our objective is to derive a very simple and rough model to assess the carbon impact of an ideal and theoretical sharing of all French operators' RAN infrastructures.

A. Assumptions

Several assumptions are required throughout section III dedicated to modeling carbon savings. All these assumptions are resumed below, for the limits of or model to be crystal clear.

1) RAN carbon impacts, including GHG scope 2 & scope 3, are proportional to the activated frequency bandwidth.
2) The traffic generated by each operator's customers on each site is proportional to the operator's market share.
3) For Quality of Experience purposes, the sum of the equivalent frequency bandwidths deployed on each site must be at least equal to a minimum threshold of available frequency bandwidth.
4) 2G and 3G download capacities are negligible.
5) Statistically, over all usages of each site, the available data rate is proportional to the available frequency bandwidth per technology.

We rely on the first assumption for scope 2 as the energy consumption of a radio cell is essentially due to its power amplifiers, which themselves depend directly on the deployed frequency bandwidth (although the real dependency may not be as linear as assumed here) [39]. The same goes for the carbon impact of the manufacturing of equipment installed on each radio site, or scope 3, as power amplifiers once again generate most of the carbon impact (if we put aside pylons).

It can safely be assumed that all 4 operators have the same demographic representation in their client base, which explains the second assumption.

The third assumption is made as, currently, RAN performance evaluation considers the peak throughput, which depends on the deployed frequency bandwidth.

The fourth assumption means that all data traffic is transmitted through 4G & 5G networks. Indeed, the decommissioning plan is underway.

Finally, let us consider the fifth assumption. Naturally, each end-user's throughput highly depends on its relative position within the radio cell. However, the study assumes the average throughput available for all users of the same cell is roughly proportional to the cell's available frequency bandwidth.

B. Business-as-usual scenario in France

This subsection describes the first steps of the mathematical model we have specified to assess carbon savings, by applying it to a single site. The final steps are presented in the next subsection III-C, whereas the generalisation of the model is presented in subsection III-G.

All variables used for the model are described in table I.

α_{F_B}	Weight associated to frequency band F_B
$AF_{F_B,i,s}$	Activated frequency bandwidth on frequency band F_B by operator i on site s
$AFO_{F_B,s}$	Frequency bandwidth activated by Orange on frequency band F_B on site s
bw_t	Minimum frequency bandwidth required to reach the target peak rate
EFB	Available equivalent frequency bandwidth for all 4 operators in France
EFB_s	Available equivalent frequency bandwidth for all 4 operators on site s
$EFBO_s$	Available equivalent frequency bandwidth for Orange on site s
$EFBO_{5,s}$	Sum of all available equivalent 5G frequency bandwidths for Orange on site s
FBS	Theoretical frequency bandwidth saving in an ideal scenario
FBS_s	Theoretical frequency bandwidth saving in an ideal scenario on site s
OMS	Orange Market Share
$P5C$	Percentage of 5G resources due to coverage extension
$PLO_{F_B,s}$	Monthly maximum load, at the peak traffic, for Orange's frequency band F_B on site s
$PRBO_{F_B,s}$	Percentage of Physical Resource Blocks (PRB) actually used over a period of 24h on site s on frequency band F_B by Orange end-users
ρ	Maximum acceptable monthly peak load $\in [0;1]$
RPA_d	Ratio of day d peak traffic to day d mean traffic
$RPA_{s,d}$	Ratio of site s peak required frequency to the average used frequency on day d
$STI(s)$	= 1 if site s 5G resources are deployed for regulatory requirements = 0 if site s 5G resources are deployed for capacity upgrade
$UFBO$	Equivalent frequency bandwidth currently used by Orange end-users in France based on real traffic statistics
$UFBO_s$	Equivalent frequency bandwidth currently used by Orange end-users on site s
UFB_4	Equivalent frequency bandwidth currently used by all mobile end-users in France
$UFB_{4,s}$	Equivalent frequency bandwidth currently used by all mobile end-users in France on site s

TABLE I
PARAMETERS TO ASSESS THE POTENTIAL OF RAN SHARING

The French National Frequency Agency, the ANFR, publishes information on all RAN sites currently deployed in France [40]. As depicted on the Figure 2, the Peillet radio site, located rue de Kerwenet Trebeurden 22560 France, is dedicated to a single operator. Such sites represented 32 431 sites out of 60 986 sites in France, thus 53,18% of the radio sites in May 2023. How antennas are shared is presented in table II below. It shows that the vast majority of antennas (84,76%) are used by a single operators. Surprisingly, more antennas are shared between 4 operators than between 3 operators. This is for example the case in the Rennes metro line, where antennas are deployed by Totem [35] and used by all 4 operators using MORAN.

Shared antennas	None	between 2 operators	between 3 operators	between 4 operators
Number	346 209	49 097	786	12 389
Percentage	84,76%	12,02%	0,19%	3,03%

TABLE II
MAY 2023 IN FRANCE, FEW ANTENNAS ARE SHARED

Trebeurden Helios	Bouygues & SFR antenna sharing		Free	Orange	Total MHz
3 500 MHz frequency band	[3570,3640] 70 MHz for 5G	[3490,3570] 80 MHz for 5G	[3640,3710] 70 MHz for 5G	[3710,3800] 90 MHz for 5G	310 MHz
2 600 MHz frequency band	[2655,2670] [2535,2550] 30 MHz for 4G	[2620,2635] [2500,2515] 30 MHz for 4G	[2670,2690] [2550,2570] 40 MHz for 4G	[2635,2655] [2515,2535] 40 MHz for 4G	140 MHz
2 100 MHz frequency band	[2125.3,2140.1] [1935.3,1950.1] 29.6 MHz for 4G & 5G	[2110.5,2125.3] [1920.5,1935.3] 29.6 MHz for 4G & 5G	[2140.1,2154.9] [1950.1,1964.9] 29.6 MHz for 4G	[2154.9,2169.7] [1964.9,1979.7] 29.6 MHz for 4G	118.4 MHz
1 800 MHz frequency band	[1860,1880] [1765,1785] 40 MHz for 4G	[1825,1845] [1730,1750] 40 MHz for 4G	[1845,1860] [1750,1765] 30 MHz for 4G	[1805,1825] [1710,1730] 40 MHz for 4G	150 MHz
800 MHz frequency band	[832,842] [791,801] 20 MHz for 4G	[842,852] [801,811] 20 MHz for 4G		[852,862] [811,821] 20 MHz for 4G	60 MHz
700 MHz frequency band	[773,778] [718,723] 10 MHz for 4G	[758,763] [703,708] 10 MHz for 4G	[778,788] [723,733] 20 MHz for 4G & 5G	[763,773] [708,718] 20 MHz for 4G	60 MHz

TABLE III
FREQUENCY BANDWIDTHS DEPLOYED BY ALL 4 OPERATORS ON HELIOS SITE, FRANCE, TREBEURDEN HARBOR DISTRICT

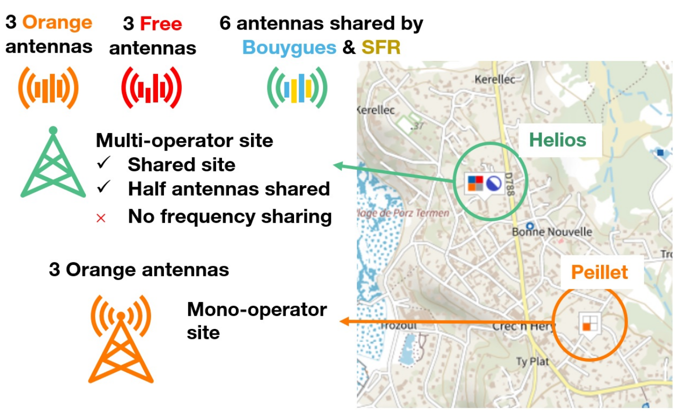

Fig. 2. Current RAN sharing in France, Trebeurden port district

Table III highlights all frequency bands and frequency bandwidths currently deployed on the multi-operator site, Helios, located rue du Dolmen in Trebeurden, 22560 France. Yet the capacity of each frequency band is not equivalent. Indeed, the 3 500 MHz frequency band corresponds to $3,5 \times 10^9$ wavelengths per second, while the 2 600 MHz frequency band corresponds to $2,6 \times 10^9$ wavelengths per second. Moreover, at first guess, the quantity of information that can be transmitted per second depends on the wavelength.

Let us thus define α_{F_B} the weight associated to frequency band F_B. Our first guess is $\alpha_{3500} = 3,5$, $\alpha_{2600} = 2,6$, $\alpha_{2100} = 2,1$, $\alpha_{1800} = 1,8$, $\alpha_{800} = 0,8$ and $\alpha_{700} = 0,7$. Nevertheless, this first guess is one of the weak point of our model that should be addressed in future studies. However, when setting all weights to 1, the results we obtain are of the same order of magnitude.

Let $AF_{F_B,i,He}$ be the activated frequency bandwidth on frequency band F_B, for operator i, on site Helios. The actually available frequency bandwidth is lower, as the acceptable load (ρ) is lower than 100%. This parameter will be discussed in section III-E. Yet, for now, let us consider $\rho = 0,5$. The available frequency bandwidth on frequency band F_B, for operator i, on site Helios is thus $\rho \times AF_{F_B,i,He}$, where $AF_{F_B,i,He}$ is given in Table III.

The currently available equivalent frequency bandwidth (EFB_{He}) by all 4 operators on this Helios radio site is thus

$$EFB_{He} = \rho \sum_{F_B} \alpha_{F_B} \sum_{Operator\ i} AF_{F_B,i,He} = 1028,82. \quad (1)$$

For Orange, we define $AFO_{F_B,He}$ as the frequency bandwidth activated by Orange on frequency band F_B on site Helios. $AFO_{F_B,He}$ is given in Table III, Orange column. The currently available equivalent frequency bandwidth ($EFBO_{He}$) for Orange on this Helios radio site is thus

$$EFBO_{He} = \rho \sum_{F_B} \alpha_{F_B} \times AFO_{F_B,He} = 291,58. \quad (2)$$

While 4 operators are present on the Helios site, we only have access to Orange's traffic statistics. We thus compute Orange's currently used equivalent frequency bandwidth on site s ($UFBO_s$), which corresponds to the total equivalent frequency bandwidth required at the site's monthly peak load. First, we derive Orange's maximum resource use over 24h (averaged over 5mn) on this Helios multi-operator site for each frequency band. Our figures corresponds to the demand in April 2024 (more precisely from March 22 to April 21, 2024). Then, for each frequency band, the used equivalent bandwidth is computed as $\alpha_{FB} \times AFO_{F_B,He} \times PLO_{F_B,He}$, where $PLO_{F_B,He}$ is the monthly maximum load, at the peak traffic, for Orange's frequency band F_B on site Helios. Thus

$$UFBO_{He} = \sum_{F_B} \alpha_{F_B} \times AFO_{F_B,He} \times PLO_{F_B,He}$$
$$UFBO_{He} = 189,79. \quad (3)$$

The deployed frequency bandwidth capacity on each site must be greater than bw_t, the minimal equivalent frequency bandwidth required to reach the target peak. Based on the ANFR data [40], we estimate this parameter as $bw_t = 5MHz$. Thus, if $UFBO_{He}$ was lower than $5MHz$, we would set it to $5MHz$.

We extrapolate $UFB_{4,s}$, the equivalent frequency bandwidth currently used by all mobile end-users in France on site s, using Orange's Market Share $OMS = 0,40$. More precisely, we estimate $UFB_{4,s}$ on the Helios site using, equation 3, as

$$UFB_{4,He} = \frac{UFBO_{He}}{OMS} = 478,48. \quad (4)$$

C. Fully cooperative scenario in France

This subsection describes the final steps of the mathematical model we have specified to assess carbon savings, by applying it to a single site. The first steps are presented in the previous subsection III-B, whereas the generalisation of the model is presented in subsection III-G.

In this fully cooperative scenario we assume radio sites, antennas and frequencies are shared. We also assume the geographical zone is covered by several overlapping RAN infrastructures. This scenario is depicted in the following Figure 3, at a local scale.

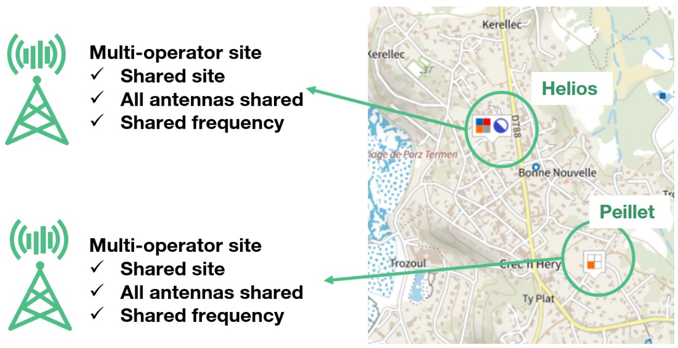

Fig. 3. Fully cooperative RAN sharing in France, Trebeurden harbor district

Based on this fully cooperative 4-MNO RAN sharing, we compute the theoretical frequency bandwidth saving on site s (FBS_s) as

$$FBS_{Helios} = 1 - \frac{UFB_{4,He}}{EFB_{He}} = 53,88\%.$$

Thus, on the geographical area covering only site Helios, according to our model, up to 53,88% of carbon and energy could be saved if RAN infrastructures were fully shared. Nevertheless, due to the limitations of our model, this figure should be understood as an upper bound. Moreover, it embeds consequences of both infrastructure sharing and reduced overdimensioning.

D. Overview of the regulatory framework

As discussed in the introduction of this article (section I), the fully cooperative scenario presented in the previous subsection III-C assumes regulation and economic contexts have evolved. This subsection thus presents the main characteristics of the current French 5G regulatory framework. It further shows that the savings obtained in the previous subsection III-C are consequences of this regulatory framework.

Indeed, numerous legal and regulatory compliance are required in the Telecom world, dealing with areas of personal data protection and privacy, network and spectrum regulation, competition law, and public procurement legislation. For example, in the public domain, frequencies are licensed to mobile operators for providing connectivity.

The public frequency licenses constraints the mobile operator to deploy a whole national coverage and a population coverage in public and in private areas (indoor and outdoor). Moreover, in France, infrastructure sharing is heavily regulated. Roaming is only authorized temporarily and frequency sharing is discouraged [41]. As a consequence, today in France the cellular coverage provided by all 4 operators is converging on almost the whole territory [42]. The presence of 4 operators on the Helios site, each deploying 4G & 5G frequency bandwidths, is another a consequence, given that infrastructure sharing is discouraged.

Furthermore, since 2022, at least 75% of radio sites must offer 240 Mbit/s or more [43]. This multiplies by 4 the objective as compared to 4G coverage requirements. The ARCEP also imposes a minimum speed of 250Mb/s on at least 75% of sites and on all roads (motorways and secondary roads) [43]. The overdimensioning of the Helios site is a consequence of these throughput requirement. Thus the potential savings relative to the fully shared infrastructure scenario, which emerge from infrastructure sharing and lesser overdimensioning, are consequences of the current French 5G regulatory framework.

In the meantime, the French agency for ecological transition scenarios suggests different objectives [44]. A joint report written with the French regulator, the ARCEP, states that "Ensuring that networks develop as a common good is ARCEP's mission" [45]. We thus expect a change in the French regulation for future generations of cellular networks is plausible, if not probable. Legislation is also likely to keep on evolving rapidly in Europe, which has committed to be climate-neutral by 2050 [46]. The #EUGreenDeal notably led to the Carbon Border Adjustment Mechanism [47], which entered into application in October 2023. Recently, the European directive on sustainability reporting, known as the Corporate Sustainability Reporting Directive [48] widens the mandatory scope of company's extra-financial reporting. Once again, this opens the road to new regulatory and economic equilibriums.

E. Impact of capacity upgrades vs regulatory requirements

The savings obtained in section III-C relative to Helios site embed both consequences of overlapping networks and high overdimensioning. Nevertheless, RAN resources may be deployed mainly for two reasons: capacity upgrade, to support traffic increase, and 5G regulatory requirements.

As an illustration, let us compute the theoretical savings due to Orange's overdimensioning on Helios site. As discussed, the parameter ρ corresponds to the maximum acceptable load. It significantly influences Orange's available frequency bandwidth. On the Helios site, with $\rho = 0,5$, Orange's available equivalent frequency bandwidth is (see equation 2) $EFBO_{He} = 291,58$. Therefore, using equation 3, $291,58 - UFBO_{He} = 101,79$ of equivalent frequency bandwidth is purely due to overdimensioning. This corresponds to 35% of the available equivalent frequency bandwidth.

Naturally, traffic increase assumptions are highly critical for dimensioning RAN infrastructures. In the past years, the Annual Mobile Traffic Increase (AMTI), expressed in % per year, has started slowing down from +96% in 2017 to +32% in 2020 according to [49]. Thus our proposal is to consider $AMTI \in [10\%; 30\%]$ for dimensioning future deployments.

Let us now use this $AMTI$ parameter to separate 5G resources deployed for capacity upgrade from the ones deployed for regulatory requirements. On each 4G & 5G radio site, we estimate that 5G resources have been deployed for capacity upgrade if the 4G capacity alone was not able to face the traffic increase over a year. Let us consider the Site Traffic Increase, $STI(s)$, a function equal to 0 if the 5G resources on the site are due to capacity upgrade, and 1 if they are due to regulatory requirements. $STI(s) = 1$ if $EFBO_s > UFBO_s \times (1 + AMTI)$, and $STI(s) = 0$ otherwise. Let $EFBO_{5,s}$ be the sum of all equivalent 5G frequency bandwidths activated by Orange on site s. The percentage of 5G resources due to regulatory requirements $P5C$ is then computed as

$$P5C = \frac{\sum_{Sites\ s} STI(s) \times EFBO_{5,s}}{\sum_{Sites\ s} EFBO_{5,s}}.$$

We implemented this model using python and the pandas library. We first carried out an analysis of sites loads, then we classified the 5G resources on site s as due to regulatory requirements or capacity upgrade according to the above explanation. In July 2023, we obtained a percentage of resources due to regulatory requirements equals to 83,4% with $AMTI$ = 30%. It thus appears that, currently, 5G RAN deployments are largely due to the current French regulatory framework. The figure should yet only be understood as an upper bound. Moreover, to our knowledge no other estimation of this ratio exists, so it needs to be confirmed by other studies. The good news is that a different regulatory framework could significantly reduce cellular networks' environmental impact without impacting end-users.

Nevertheless, the model presented here is very rough and neglects many operational constraints, including Quality of Service (QoS) requirements. It also neglects the fact that RAN resources are deployed to support traffic increase over the whole lifetime of RAN equipment, which is 6 to 7 years. As the model presented in the previous subsections III-B and III-C has the same limits, it explains why the savings obtained on the Helios site are so high. It also indicates that savings enabled by fully sharing RAN infrastructures, based on our model, applied at the whole French territory scale, could be of the order of magnitude of 80%.

F. Extrapolate the peak load from the average load

Before generalising the model presented in subsection III-B and III-C, another constraint has to be explained. Indeed, the monthly maximum load, at the peak traffic, of Orange's frequency band F_B on site s ($PLO_{F_B,s}$) is not directly available. Only Orange's daily average load on frequency band F_B on site s is available. For each considered day, we therefore have to extrapolate the daily peak load from the average load.

Let $PRBO_{F_B,s}$ be the percentage of Physical Resource Blocks (PRB) actually used by Orange over a period of 24h on site s and frequency band F_B. As no database directly gives us $PLO_{F_B,s}$, we adopt a pragmatic approach and rely on the data we have access to. Let us consider the ratio of site s peak required frequency to the average used frequency on day d, $RPA_{s,d}$. To derive $PLO_{F_B,s}$, from $PRBO_{F_B,s}$, we need to estimate $E(RPA_{s,d})$, the average value of the $RPA_{s,d}$ on site s over a year. The peak percentage of usage of PRB is thus estimated as $E(RPA_{s,d}) \times PRBO_{F_B,s}$, and the peak required frequency as $PLO_{F_B,s} = E(RPA_{s,d}) \times PRBO_{F_B,s}$.

To determine $E(RPA_{s,d})$, the best option would be to use a dataset representing the evolution of the percentage of used PRB over 24h on site s. Unfortunately, we were unable to find such data. To overcome that issue, we had to rely on the assumption (5) presented in section III-A.

Our model approximates the ratio of site s peak required frequency to the average used frequency over 24h as the ratio of site s peak data rate to the average data rate over 24h. Our estimation is then based on data corresponding to the aggregation of all mobile traffic on all French sites every day: RPA_d, for day $d = 1$ do $d = 365$. We then compute RPA_d as the ratio of the day d peak traffic to day d mean traffic, over 365 different d days. Our estimation being likely to hide local discrepancies, we rely on the upper bound of $E(RPA_d) + \sigma(RPA_d)$ to estimate $E(RPAs, d)$ as $E(RPA_d) + \sigma(RPA_d) \approx 1.90$. In other words, the ratio of the peak load to the average load is upper bounded by 1,90. According to our observation, this ratio is stable over a year, independently from the traffic increase observed in parallel. Figure 4 depicts more information on the distribution of RPA_d.

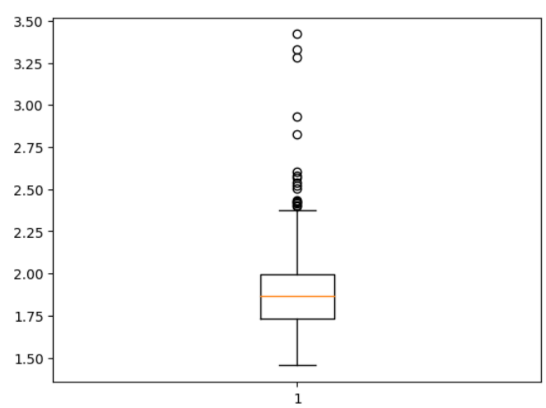

Fig. 4. RPA_d blox pot

We thus approximate $PLO_{F_B,s}$ as

$$PLO_{F_B,s} \approx 1,90 \times PRBO_{F_B,s}. \quad (5)$$

The limit of this approximation is that we compute the mean on all sites over a complete year, whereas the mean should be computed on each site and each frequency band separately.

Moreover, as traffic increases during the busiest period in the same proportion as during the rest of the day, our counter-intuitive observation, open to debate, is that traffic demand outside the peak hour would have as much impact as traffic demand during the peak hour.

We can also observe that, on Helios site, only $100-53,88 = 46,12\%$ of physical resources are actually used, at the peak, in April 2024. On average over a day, according to Figure 4, only $\approx 46,12/1.6 \approx 29\%$ of physical resources are actually used. There is thus a huge potential for a more efficient use of bandwidth resources.

G. Assess savings between the 2 scenarios

This subsection extrapolates the very methodology exposed in section III-C at a larger scale: the French territory.

The currently equivalent activated frequency bandwidth by all 4 operators on the whole French territory is the weighted sum of all 4G & 5G frequency bandwidths, for all French operators, in all radio sites currently deployed. Now considering the maximum acceptable load on any site is given by ρ, the currently available equivalent frequency bandwidth (EFB) on the whole French territory is

$$EFB = \rho \times \sum_{Sites\ s} \sum_{F_B} \alpha_{F_B} \sum_{Operator\ i} AF_{F_B,i,s}. \quad (6)$$

Let us now compute the currently used frequency bandwidth by Orange end-users, $UFBO$ as

$$\sum_{Sites\ s} max \left(\sum_{F_B} \alpha_{F_B} \times AFO_{F_B,s} \times PLO_{F_B,s}; bw_t \right). \quad (7)$$

We extrapolate UFB_4, the currently used equivalent frequency bandwidth for all 4 operators in France, using Orange's market share $OMS = 0,40$. More precisely, we estimate UFB_4 as

$$UFB_4 = \frac{UFBO}{OMS}. \quad (8)$$

Finally, we compute the theoretical frequency bandwidth saving (FBS) of RAN sharing in the ideal scenario as

$$FBS = 1 - \frac{UFB_4}{EFB}. \quad (9)$$

To implement this model we used python and the pandas library. Our figures corresponds to the demand in April 2024 (more precisely from March 22 to April 21, 2024). The first step was to match Orange and ANFR data [40] thanks to their GPS coordinates. This matching process allowed us to utilize both sites loads and bandwidths to calculate the carbon saving by performing the above calculations.

With this model we estimate a saving of 79%, applicable to all phases of the RAN lifecycle, including for instance the purchase of network equipment (scope 3) and the energy required during the running phase (scope 2). Nevertheless, given that our modeling is very rough and neglects many operational constraints, this figure should only be understood as an upper bound.

Indeed, we have neglected several consequences of sharing RAN infrastructures. In particular, different equipment may be required. Moreover, this figure is only true on a territory covered with overlapping and overdimensioned networks.

Our model should also be enhanced considering that signalling traffic induces around a 10% PRB load on all sites. This in-compressible signalling traffic is accounted in our study. Nevertheless, we believe this in not an issue as this would increase the saving.

The saving estimated with our model is high due to the current overdimensioning of radio resources. It confirms the order of magnitude highlighted in subsection section III-E: fully sharing RAN infrastructures, based on our model, applied at the whole French territory scale, would allow 80% savings.

It should nevertheless be understood as an upper bound of the savings. Moreover, such saving seems unreachable on a large scale without a change in the regulatory framework. Still, some savings are possible where MNOs agree to cooperate and share infrastructure resources.

IV. A NEW INDICATOR, THE SUFFICIENCY DEPLOYMENT INDEX

The power usage efficiency indicator is commonly used to compare different datacenter technical environments. This indicator is always greater than 1, which corresponds to the theoretical minimum, not achievable in practise. To our knowledge, there is no equivalent to compare RAN technical environments.

A. Estimate carbon footprint and energy consumption

As we have seen in section III-D, in France 5G RAN deployments are currently triggered by the regulatory framework. Thus we believe a new regulation scheme could significantly reduce RAN environmental footprint. To do so, we define the Sufficiency Deployment Index (SDI), computed on a geographical zone G, as

$$SDI_G = \frac{\sum_{s \in G} UFB_{4,s}}{\sum_{s \in G} EF_{B,s}}. \quad (10)$$

This indicator could be used to compare RAN technical environments, including before their deployment, within a larger set of indicators to be taken into account simultaneously.

This indicator has the advantage of addressing both equipment carbon footprint (scope 3) and energy consumption (scope 2). While achieving the targeted scope 3 reductions will inevitably lead to less hardware deployments, there are other levers when focusing on scope 2, as debated below.

B. Levers specific to energy consumption

Several initiatives are addressing the energy consumption issue. Indeed, given that RAN networks are dimensionned for the peak load, which corresponds to 1,6 to 1,9 times the average load (see Figure 4), at least $1/1,6 \approx 62\%$ of frequency resources would be unused, even with $\rho = 1$. Therefore, outside of the peak hour, operators can cooperate for even more energy saving, without impacting end-users.

Moreover, during the running phase, the energy consumption can be monitored, together with the instantaneous percentage of renewable energy.

In the future, network automation could allow redesigning networks on-demand based on usage predictions and depending on the operators' will to cooperate. Such automation could address simultaneously multiple objectives including reducing the energy consumption, favour low-carbon energy mix, while ensuring that users' experience is not degraded. For instance, given that cellular networks consume energy even when there is no traffic, cooperation during the running phase could lead to important energy savings [50].

In the AI-powered cooperation for efficient networks project [51], each operator estimates the expected demand in each area during the off-peak hours that are subject to power efficiency optimization. Based on this demand, a decision of reorchestration of coverage resources (switch on/off a RAN) is made on whether to take a specific MNO's coverage area into consideration in the algorithm. Demand can be calculated using different methods, for example using only data volume measurements as described in the energy efficiency calculation in 3GPP TS 28.310 in clause 6.1.1 [52]. More precisely, two metrics are considered for demand assessment: the average number of active subscribers in a specific area and the average traffic as a sum of uplink and downlink traffic (in Gbps). Based on the historical information of the metrics, traffic predictions are generated using either statistical methods (moving average, linear regression) or AI/ML powered mechanisms for forecast generation. The project uses a forecasting generator based on enhanced "Prophet" algorithm implementation that takes into consideration historical data and generates predictions, taking into consideration seasonality, trends, holidays, and other aspects of the forecasted time series. In the current solution, demand is precalculated and available as a single read only measurement in resource performance management for each individual MNO and area.

V. Conclusion and next steps

This article highlights a first rough estimation of carbon savings that could be possible thanks to RAN sharing, without impacting end-users. The study started to feed a much larger multi-dimensional model, representing all economic sectors worldwide, under construction by Carbone4 [53]. In such context, we privileged a simple model relying on few parameters, as presented here. Yet it would need to be enhanced, for example by adopting a consequential approach. In particular, the field operations needs should be added, including the number of kilometers travelled by car for maintenance or repair, civil engineering, masts and pylons. Understanding the impact on RAN equipment purchase, given that they would have to be compatible with RAN sharing, is also required. With such an approach, the savings estimations could be much lower. Moreover, the weight associated to each frequency band is one of the weak point of our model that should be addressed in future studies. However, if we set all weights to 1, our model estimates the same order of magnitude of savings, around 80%.

During the study, a counter-intuitive observation, open to debate, was made: traffic demand outside the peak hour would have as much impact as traffic demand during the peak hour. Furthermore, given the frequency bandwidth use is currently low, efficiency alone could allow large gains.

This article confirms that sharing network infrastructures among several operators is inevitable for the telecommunication sector to reach its net zero ambitions. It shows that, in radio access networks, several technical solutions are already operational. Thus currently the main obstacles to RAN sharing are the regulatory framework and the operators' business models. Indeed, the current French regulation framework, which includes coverage and performance requirements, leads to overlapping networks and high overdimensioning. The savings highlighted in this paper embed the consequences of both. The regulatory framework will likely evolve in the coming years. We hope the SDI indicator we suggest will contribute to the emergence of new regulatory frameworks embracing environmental impacts.

However this raises a key question: how could telecommunication companies differentiate if they were to rely on the same infrastructure? Indeed, how to change operators' business models seems more challenging. A single actor cannot change its business model alone. To move on, the telecommunication ecosystem needs to understand the value for all actors of the ecosystem. Hopefully, the regulatory framework will provide new opportunities.

This study also intends to indirectly address the societal stakes. Indeed, several studies highlight the need to make collective choices on the evolution of our lifestyles in the coming decades, thus pointing out a societal issue [44]. However, for them to be informed, these choices need bio-physical models representing the constraints underlying the different lifestyle evolution scenarios. The study presented here intends to feed such scenarios, such as the one under study by Carbone4 [53], and thus indirectly to feed the societal debate.

Further study shall focus on the impact of RAN sharing on each MNO's carbon footprint, which depends on the contracts established between actors. In particular, the tower company leasing RAN resources to MNOs must report 100% of the RAN carbon footprint. Leased assets are indeed part of scope 3. It can nevertheless assess the carbon emissions potentially avoided thanks to its leased assets using the ITU-T L.1480 recommendation [54]. As illustrated in [55], such assessment needs to be carefully and deeply studied.

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