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Research article / *Article de recherche*

Energy in the heart of EM waves: modelling, measurements and management / *L'énergie au cœur des ondes électromagnétiques : modélisation, mesures et gestion*

Extensive 5G measurement campaign to monitor EMF exposure in France

Vaste campagne de mesures 5G pour surveiller l'exposition aux ondes éléctromagnétiques en France

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Abstract. As part of its mission to monitor public exposure, the French National Frequency Agency (ANFR) has launched an extensive measurement program at nearly 2000 sites to assess exposure following the deployment of the new 5G mobile technology starting at the end of 2020. For each site identified in the program, an initial measurement was conducted prior to the deployment of 5G, followed by two additional measurements after the sites had been in operation for approximately 4 months and 8 months, in order to monitor the evolution of exposure as a function of traffic growth and operational deployment. The measurements were performed in accordance with the ANFR protocol referenced in the French Official Journal, which is the reference text for accredited laboratories carrying out field measurements (E in situ). In addition to the global and detailed frequency exposure measurements, specific measurements were made by downloading a 1 GB file on the 3500 MHz band. This approach allows to artificially generate additional traffic according to the exposure indicator proposed by ANFR for steerable beam antennas and to estimate the local exposure level that would statistically be reached by 5G in the long term.

Résumé. Dans le cadre de ses missions de surveillance de l'exposition du public aux ondes électromagnétiques, l'Agence nationale des fréquences (ANFR) a lancé un vaste programme de mesures sur près de 2000 sites pour évaluer l'exposition à la suite du déploiement de la nouvelle technologie mobile 5G dès fin 2020. Pour chaque site identifié dans le programme, une mesure initiale est réalisée avant le rajout de la 5G sur ces sites, une deuxième et troisième mesure sont réalisées à environ 4 mois et 8 mois de mise en service dans le but de suivre l'évolution de l'exposition en fonction du déploiement opérationnel et de l'accroissement du trafic. Les mesures sont réalisées selon le protocole de l'ANFR référencé au Journal Officiel, constituant le texte de référence des laboratoires accrédités qui réalisent des mesures sur le terrain (E in situ). En complément des mesures d'exposition globale et détaillées en fréquences, des mesures spécifiques ont été effectuées en téléchargeant un fichier de 1 Go sur la bande 3500 MHz. Ce mode opératoire permet de générer artificiellement un trafic supplémentaire correspondant à l'indicateur d'exposition proposé par l'ANFR pour les antennes à faisceaux orientables et permet d'estimer le niveau d'exposition local qui serait statistiquement atteint à terme en 5G.

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Keywords. Exposure to EMF, 5G, Exposure monitoring.
Mots-clés. Exposition aux ondes électromagnétiques, 5G, Surveillance de l'exposition.
Note. This article follows the URSI-France workshop held on 21 and 22 March 2023 at Paris-Saclay.
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1. Introduction

5G is now being deployed in mainland France on several frequency bands: the so-called low-frequency bands 700 MHz and 2100 MHz, which have been used for many years by previous generation mobile phone networks (3G and 4G), and the new 3500 MHz band, which offers a wider bandwidth for higher data rates.

The French Frequency Agency (Agence nationale des fréquences ANFR) ensures compliance with the limits for public exposure to electromagnetic waves set by decree [1]. To this end, it develops and updates the exposure measurement protocol. As part of its mission to monitor public exposure, the ANFR has launched a major program of in situ electric field measurements to characterize the impact of 5G on exposure levels [2]. This huge operation covered almost 2000 radio stations throughout mainland France. From the end of 2020 to the end of 2021, three phases were carried out at sites identified to host 5G: an initial measurement before the arrival of 5G at these sites (phase 1), a second measurement carried out about 4 months after the start of service (phase 2) and finally a third measurement at an interval of about 8 months (phase 3). This campaign continued in 2022 and 2023 with 4 additional phases.

This paper focuses on the results up to the end of 2021 and includes a global exposure assessment based on broadband measurements, a detailed frequency assessment to obtain the contribution of each frequency band, and specific measurements with forced traffic in the 3500 band.

2. Measurement protocol and locations

2.1. *Measurement protocol*

Since 2001, the ANFR has been responsible for defining and updating the in situ measurement protocol to verify that the radiofrequency (RF) exposure levels of the general public are in compliance with the French exposure limits. The ANFR protocol is referenced in the French Official Journal [3] and is used by ISO IEC 17025 [4] accredited laboratories. It complies with the international standard EN IEC 62232 [5] section 6.3 "Evaluation processes for in situ RF exposure assessment".

The current ANFR measurement protocol version 4 was used [6]. A global measurement covering all significant radio sources between 100 kHz and 6 GHz is made at the selected measurement point. It is based on the use of a broadband probe with a sensitivity of 0.38 V/m. This assessment shall be made using a spatial averaging over a minimum of three heights (1.1 m, 1.5 m and 1.7 m) and a time averaging over 6 min (a shorter duration may be sufficient as long as the root mean square (RMS) average remains stable).

A detailed measurement (case B) can then be made at the same position as in case A to determine the exposure for each frequency band and for each operator (detailed measurement of each exposure contribution in the same frequency range). Case B involves the use of a spectrum analyzer with a minimum sensitivity of 0.05 V/m per frequency band. The results include the integration per service (e.g., mobile phone band or TV band) and the sources of concern per service that are defined as a significant emission with a minimum level of 0.3 V/m (more than

Figure 1. Typical configurations of measurement.

40 dB below the lowest regulatory limit). Spatial averaging over at least three heights (1.1 m, 1.5 m and 1.7 m) and temporal averaging over 6 min is also required for Case B (the root mean square (RMS) of the E-field measured at the three heights over 6 min).

In the framework of this campaign, case B was not systematically performed at every measurement point. During the second phase of measurements in 2021, it was mostly carried out only at points where the global level was greater than or equal to 2 V/m.

All measurements were performed outdoors and during daytime, in direct view of the main lobe of the antennas (line-of-sight) and at a distance of about 100 m. Figure 1 shows a typical configuration of this campaign.

For the current uses of the previous technologies (2G/3G/4G), the level measured with a broadband probe (case A) is a good indicator of exposure regardless of the time of day, and is generally close to the level observed with continuous measurements averaged over a period of 6 min: the amplitude of the variations observed in the studies during the day is generally small, less than 30%. However, with the 5G steerable beam antennas, greater spatial and temporal variability is expected. As a result, the level measured with a broadband probe at any one time may no longer be a good indicator of exposure. The level of exposure will strongly depend on the usage, and in particular on the data request made by the terminal. For this reason, ANFR proposed in [7], a new indicator, based on a foreseeable use of 5G. This consists of sending 1 GB of data every 6 min in a given direction. Assuming an average data rate of 500 Mbps, the antenna will only transmit in the given direction for about 15 s out of the 6 min (about 4% of the time).

At the beginning of the roll-out of a new technology, the load is low, mainly because only a few users have the appropriate terminals and subscriptions. Thus, when 5G was launched in the 3.4–3.8 GHz band, which is used exclusively for 5G, the levels measured were very low, as expected, because the 5G network would be very lightly loaded. In order to measure an exposure level that might be more representative of what 5G will eventually generate in the long term, the ANFR opted to voluntarily solicit the 5G antennas by downloading a 1 GB file in order to consider a realistic antenna load according to the assumptions made to define the exposure indicator described above.

The measurement consists of two assessments in the 3500 MHz band: when the network is not voluntarily solicited and when it is solicited by a mobile phone by downloading a 1 GB file

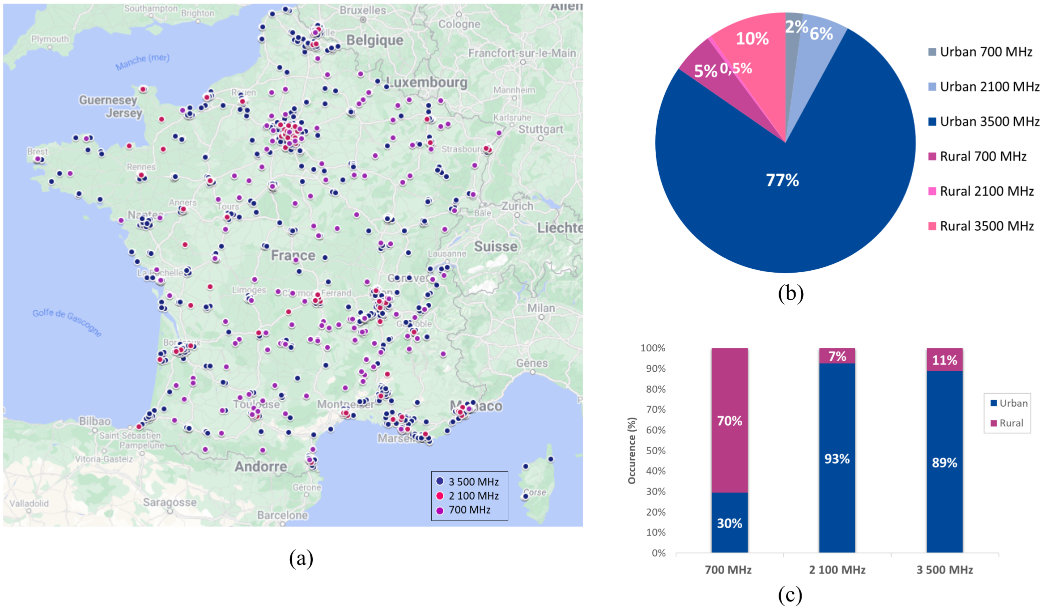


Figure 2. (a) Geographical distribution. (b) Environment type distribution. (c) Frequency bands distribution.

from a server, ensuring that the server's performance allows the expected 5G speeds (500 Mbps on average) at the measurement point. It is also necessary to ensure that the download occurs in the 3500 MHz band. This approach for in situ measurements using emulated base station load profiles is described in Annex B of the IEC 62232 standard [5].

It is worth noting that the RMS electric field level averaged over 6 min without network solicitation can be evaluated over a period of less than 6 min, as long as the averaged RMS value is stable. The RMS electric field level averaged over 6 min can then be evaluated from the measurement averaged over the duration of the download according to the following equation:

$$E_{\text{estim\_6 min}} = \sqrt{\left(\frac{T_t}{360}\right) \times E_{\text{at}}^2 + \left(1 - \frac{T_t}{360}\right) \times E_{\text{st}}^2} \tag{1}$$

where:

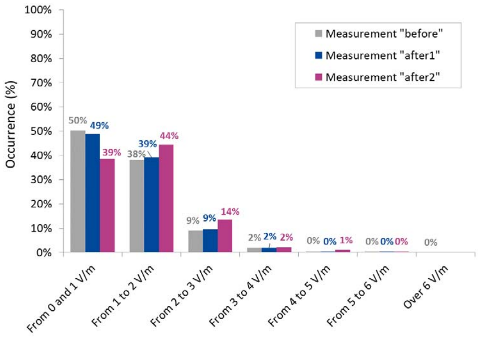
$E_{\text{estim\_6 min}}$: field strength in V/m averaged over 6 min
T_t: duration of the 1 GB file download in seconds
E_{at}: average field strength in V/m measured during the download time
E_{st}: average field strength in V/m measured without artificial network load.

2.2. *Measurement locations*

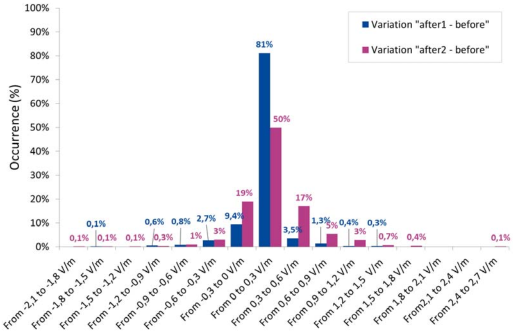
The distribution of 5G sites in mainland France is shown in Figure 2(a)[1], with 85% of sites located in urban areas and 15% in rural areas (Figure 2(b)). This distribution is close to the share of urban population in the total population of France (80% in urban areas) [8].

In the remainder of this paper, a measurement taken before 5G was activated will be noted as a "before" measurement, representing Phase 1, the one performed after approximately 4 months of 5G activation will be noted as an "after 1" measurement, representing Phase 2, and

[1] From 2022, the ANFR has extended its program to include the DROM-COM.



(a)



(b)

Figure 3. (a) Distribution of overall exposure levels before and after 5G roll out on 3500 MHz band; (b) distribution of differences between overall exposure levels before and after 5G roll out on 3500 MHz band.

the one performed after approximately 8 months of operational deployment will be referred to as an “after 2” measurement, representing Phase 3. Depending on the phase of the campaign considered, a pair of measurements taken before and after 5G is activated will be recorded as “before–after1” or “before–after2”. A trio of measurements representing the three phases of the campaign will be noted “before–after1–after2”.

3. Results

3.1. *Analysis of the overall exposure levels on sites hosting 5G in the 3500 MHz band*

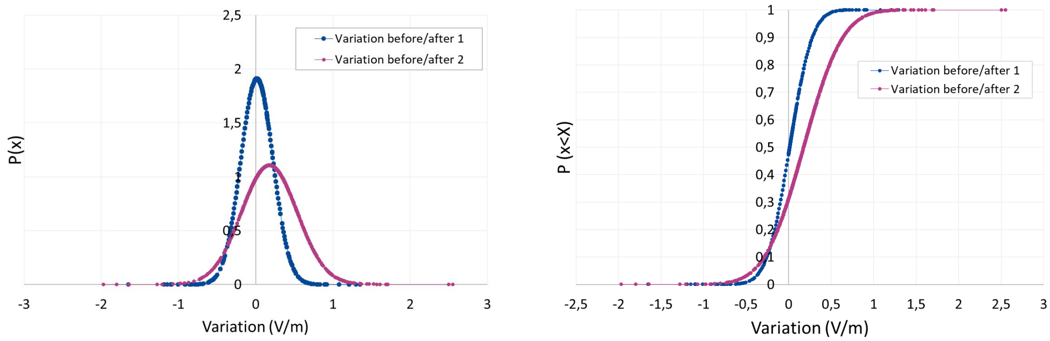
In this section, the analysis of the overall exposure levels (case A) is studied at about 1360 sites hosting 5G in the 3500 MHz band. Figure 3(a) shows the distribution of measurements by 1 V/m increments on the overall exposure levels observed before and after the activation of 5G during phases 2 and 3 of the campaign.

These histograms show that exposure remains steady between phases 1 and 2. This trend has changed in phase 3, where an increase is observed. In fact, 11% of the points that were in the “from 0 to 1 V/m” range in phase 1 leave this range and move to the higher ranges because they become more exposed, as can be seen from the histograms plotted in Figure 3(a). However, this increase is moderate, as can be seen, 83% of the “after2” measurements remain below 2 V/m, compared to 88% of the “before” and “after1” measurements.

This first conclusion is confirmed by a comparison of the statistical parameters shown in Table 1. The average exposure levels are 1.16 V/m for the “before” measurement, 1.17 V/m for the “after1” measurement and 1.34 V/m for the “after2” measurement, i.e., an average variation that increases from 0.01 V/m (close to zero) for phase 2 to 0.18 V/m for phase 3.

In order to better characterize the variation between the “before” and “after1–after2” measurements, the local variation is studied to observe how the electric field levels are distributed locally (i.e. site by site). For this purpose, the statistical distribution of the differences between the trio of “before–after1–after2” measurements is characterized by histograms of 0.3 V/m steps in Figure 3(b) and modeled by the normal distribution probability density and its cumulative distribution function (CDF) in Figure 4.

The histograms show a greater variation in phase 3 than in phase 2, where in more than 90% of the cases, the variation was between −0.3 V/m and 0.3 V/m (non-significant), compared to 69%



(a) (b)

Figure 4. Probability density function (a) and cumulative distribution function (b) of differences between overall exposure levels before and after 5G roll out on 3500 band. See Figure 3(b) for real data.

Table 1. Comparison of overall exposure filed level statistics before and after 5G roll out

	Nb measurements	Mean (V/m)	Median (V/m)	Std Deviation (V/m)	Max (V/m)
Overall exposure "before"	1358	1.16	0.99	0.75	6.19
Overall exposure "after1"	1358	1.17	1.01	0.74	5.41
Overall exposure "after2"	1358	1.34	1.19	0.79	5.83
	Nb measurements	Mean variation	Median variation	Std deviation variation	Max variation
"after1–before" Variation	1358	0.01	0.02	−0.01	−0.78
"after2–before" Variation	1358	0.18	0.2	0.04	−0.36

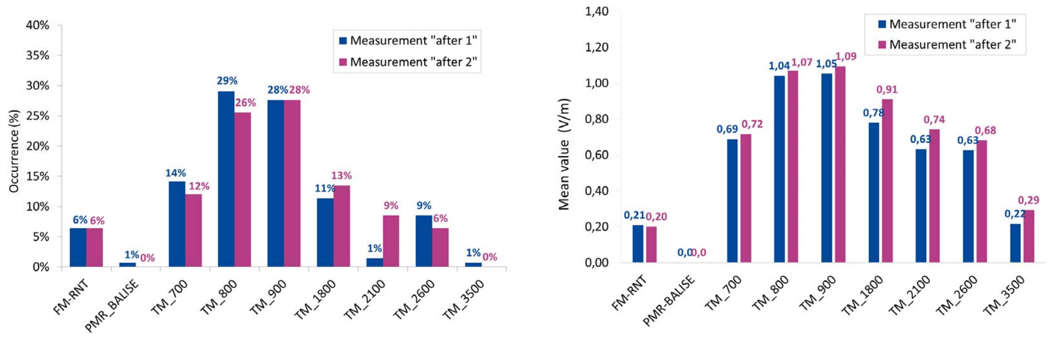
in phase 3. From the probability density and CDF, it can be clearly seen that the distribution of the "before–after2" variation is no longer centered on zero as it was for the "before–after1" variation. It also shows that the 90% and 99% values are larger for the "before–after2" variation.

The results conclude that 4 months after 5G became operational, there was no significant change in overall exposure compared to before 5G started. However, after 8 months, an increase in overall levels was observed: the average overall exposure level increased from 1.16 V/m to 1.34 V/m.

It should be further noted that as only the global exposure was investigated, it is not possible at this stage of the study to identify which frequency bands are contributing to this increase. The detailed frequency measurements (case B), discussed in the next section, provide a comprehensive exposure assessment with a frequency-selective analyzer that can identify the sources contributing to the exposure, as described above in the measurement protocol.

3.2. *Analysis of the contribution of the 3500 MHz band*

For a more detailed analysis of the increase highlighted in the case A study, the detailed frequency measurements (case B) will be discussed by isolating the contribution of the telephony service in the 3500 MHz band, but also in the other frequency bands. Among the 1358 sites previously analyzed, 141 of the most exposed sites (where at least one measurement has an overall value of 2 V/m) were covered by detailed measurements during phases 2 and 3 of the campaign.



(a) (b)

Figure 5. Distribution of main contributions to overall exposure (a) by service/frequency band and evolution of their mean value (b). (FM-RNT: Radio broadcasting, PMR-Balise: Private Mobile Radio, TM: Mobile Telephony (cellular network).)

Firstly, the Figure 5(a) shows the service contributing most to the overall exposure, where it can be seen that the 800 MHz and 900 MHz bands are the main contributors in about 55% of the cases in both phase 2 and phase 3. The 2100 MHz band appears to be the main contributor in 9% of cases in phase 3, compared to 1% in phase 2. The 3500 MHz band could not a priori be the cause of the increase in total exposure in phase 3 as it is not the main contributor.

Secondly, to better illustrate the exposure by service, the histograms in Figure 5(b) show the increase in average exposure, particularly for mobile services, between phases 2 and 3. The increase in average exposure per frequency band is relatively significant for frequencies where LTE (4G) is present (TM_1800 and TM_2100). For the 3500 MHz band, it is not possible to conclude that there is an increase as the levels are not significant. It is important to point out that the levels measured remain very low compared to the regulatory limit values (36 V/m for the lowest mobile telephony band and 61 V/m for the highest band).

At least, these selective E-field measurements show that the observed increase in total exposure is not due to an increase in field strength in the 3500 MHz band, but to an increase in exposure in the other mobile phone bands, especially those allocated to 4G.

3.3. *5G specific measurements with data download*

At the launch of the campaign, few users are soliciting 5G antennas, so it seemed interesting to artificially generate traffic to study the impact of 5G on overall exposure by simulating higher usage in this band. As described in the protocol section, the traffic is generated by downloading 1 GB of data, which is equivalent to the exposure indicator proposed by the ANFR. Measurements from 464 sites are studies in this section.

Figure 6 shows in grey the average field strength during the download of the 1 GB file in the 3500 MHz band, and in pink and blue the levels over 6 min with and without artificial download. The levels with download averaged over 6 min are calculated from Equation (1) using the download time and the mean level measured during the download.

For each site, the levels shown here are the maximum levels observed between phases "after1" and "after2".

The mean increase calculated between the measurement on the 3500 MHz band with artificial download averaged over 6 min (shown in blue) and the average level without download (shown in pink) on the same band is 0.54 V/m. The average level calculated from the single download

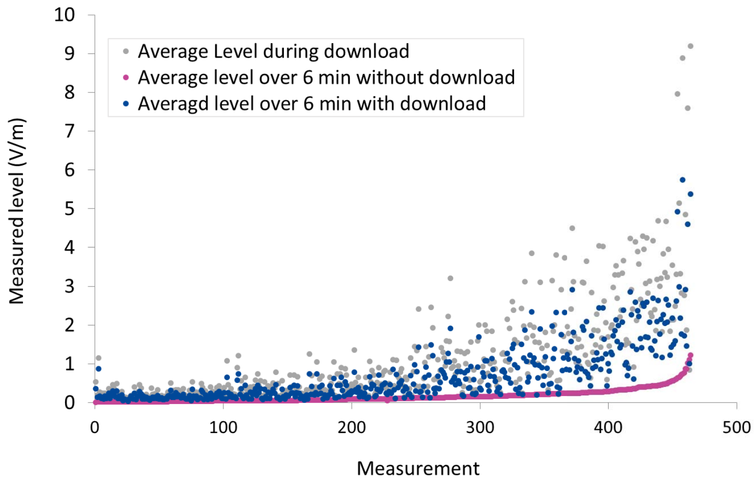


Figure 6. Average field strength while downloading a 1 GB file compared with the average level without downloading on the 3500 MHz band.

Table 2. Statistics on the 3500 MHz band with and without downloading

	Nb measurements	Mean (V/m)	Median (V/m)	Standard deviation	Max (V/m)
Exposure on the band 5G 3500 MHz without download	464	0.16	0.10	0.16	1.22
Exposure on the band 5G 3500 MHz with download	464	0.70	0.38	0.79	5.75
	Nb measurements	Mean variation	Median variation	Std deviation variation	Max variation
Variation with and without download (V/m)		0.54	0.28	0.63	4.53

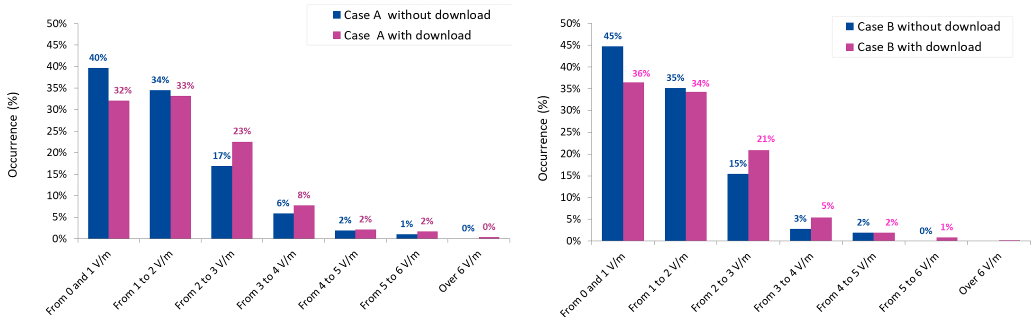
of the 1 GB data file is 0.68 V/m, close to 0.70 V/m, almost the same as the average level from the download measurements including existing traffic, suggesting no significant traffic yet in this band.

The Table 2 shows the statistics calculated for the 3500 MHz band with and without artificial downloading.

To evaluate the impact on the global exposure level, the average level over 6 min related to the download of the isolated 1 GB file, resulting from the specific measurement with 5G artificial solicitation, is integrated by calculation to the global exposure case A and the cumulative overall exposure case B without specific solicitation of the network (only with existing traffic). The Figure 7(a) shows the distribution of the overall exposure levels "case A" with and without artificial downloading. The Figure 7(b) shows the distribution of the overall cumulative exposure "case B" with and without artificial downloading.

The comparison between the statistical parameters of case A and case B with and without downloading in the 3500 MHz band is shown in Table 3.

The average increase observed between the global exposure without downloading a file (only with existing traffic) and the global exposure relative to the single download of the 1 GB file is



(a) (b)

Figure 7. Distribution of the overall exposure (case a) (a) and overall cumulative exposure (case B) (b) with 5G solicitation computationally integrated and compared to the measurement without specific solicitation (with existing traffic only).

Table 3. Comparison of field strength statistics of overall exposure with and without downloading at 464 sites operating on 3500 MHz band

	Number of measures	Average (V/m)	Median (V/m)	Standard deviation
Overall exposure case A without download	464	1.51	1.24	1.00
Overall exposure case A with download	464	1.74	1.53	1.12
Variation (V/m)		0.23	0.29	0.12
Overall cumulative exposure case B without download	464	1.33	1.13	0.89
Overall cumulative case B with download	464	1.58	1.38	1.03
Variation (V/m)		0.25	0.25	0.15

21% (0.23 V/m) for case A and 31% (0.25 V/m) for the cumulative level for case B, in line with the exposure indicator introduced by the ANFR [9].

In fact, in order to assess the use of the 3500 MHz band with respect to the indicator proposed by ANFR, based on the expected use of 5G (1 GB of data sent in a given direction every 6 min), the relative usage rate is calculated from the level measured in the 3500 MHz band without download (corresponding to the existing traffic) and the level measured in the 3500 MHz band with download (corresponding to the estimated future traffic). This rate reached an average of 12% (median 6%), which means that the exposure indicator proposed by ANFR remains relevant and has not yet been reached (it would be reached when the rate reaches 100%). This means that 5G usage in the 3500 MHz band was still low at the end of 2021.

3.4. *Results on sites hosting 5G on low bands (700 MHz and 2100 MHz)*

It should be noted that these frequency bands are not reserved exclusively for 5G, the resources are shared with 4G technology and the measurement equipment does not allow to distinguish the 5G contribution from the 4G contribution in the level measured in the band.

To study the exposure created by the 5G roll out in these bands, 101 sites deploying 5G in the 2100 band and 142 sites in the 700 band were measured three times: an initial measurement before 5G deployment corresponding to phase 1 ("before"), and two measurements after 4 and 8 months of operation, corresponding to phase 2 ("after 1") and phase 3 ("after 2") respectively.

Regarding the 700 MHz sites, the overall level results show an average increase in overall exposure of 0.1 V/m between September and December 2021 (during phase 3) compared to an increase of 0.06 V/m at the same sites between May and September 2021 (during phase 2).

The statistics for the overall exposure levels measured at the 2100 MHz 5G sites exposure remained stable between phases 1 and 2 (average variation of −0.02 V/m). An upward trend was observed in phase 3 (average variation of 0.11 V/m).

In sum, as for measurements on 3500 MHz sites, the results of the low band measurements show an increasing trend in the overall exposure level during the period of the end of 2021.

The analysis of the detailed frequency measurements reveals that the 800 MHz, 900 MHz and 1800 MHz bands are the main bands contributing to the overall exposure.

4. Conclusion

This paper focused on analyzing the exposure evolution related to the deployment of 5G on the French national territory. More than 5000 measurements were part of a large exposure monitoring program on sites deploying 5G in the 700 MHz and 2100 MHz low frequency bands already used for 3G and 4G networks, as well as in the new 3500 MHz band exclusively dedicated to 5G. This paper was dedicated to the results of measurements performed on sites deploying 5G during the year 2021.

First, the analysis of the overall measurements allowed to observe a slight increase on 1358 sites, measured at 4 months and then 8 months intervals after their 5G deployment. Then, a sample was taken of the most exposed sites, where the analysis of detailed measurements showed an increase in the average exposure on all the mobile telephony bands. It also showed that the 800 MHz and 900 MHz bands are the main contributors to exposure, followed by the 700 MHz, 1800 MHz, 2600 MHz, 2100 MHz and 3500 MHz bands respectively for phase 2 and the 1800 MHz, 700 MHz and 2100 MHz bands respectively for phase 3 (the 3500 MHz band was not identified as the main contributor in phase 3).

As 5G traffic is still low at this stage of deployment, additional 5G specific measurements were performed in the 3500 MHz band in the presence of artificially generated traffic to solicit the 5G antenna by downloading a 1 GB file using a 5G phone. The first results suggest an increase of about 30% of the overall exposure.

It can be conclude that the increase in the overall levels at 5G 3500 MHz sites is not a priori related to an increase in the field strength in this band, but to an increase in levels in all other frequency bands of mobile telephony, reflecting an increase in traffic. It is important to remember that phase 3 of the campaign took place at the end of 2021 where an increase in traffic could be observed.

The results of the low band measurements also show an increasing trend in overall exposure levels by the end of 2021. The average increase is 0.11 V/m for 5G sites operating in the 2100 MHz band, and 0.09 V/m for sites deploying 5G in the 700 MHz band. The frequency analysis showed that this increase is not correlated with the deployment of 5G in these bands.

The measurement campaign has continued in 2022 and 2023 and will assess exposure after 1 to 2 years of 5G deployment.

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

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