UNIVERSITY OF ROME TOR VERGATA

Faculty of Engineering

Engineering Sciences Degree Course

Degree Thesis

POWER AND ELECTROMAGNETIC FIELD COMPUTATIONAL ANALYSIS OVER LONG-TERM PRE-5G VS 5G EXPOSURE TRENDS

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A.Y. 2021-2022

Abstract

Massive deployment of advanced wireless networks is essential to support broadband, low-latency communications, and IoT applications. 5G service is already available in many countries, around the world. Currently, 5G networks are operated in parallel with already deployed pre-5G networks (including 4G). In this work, we focus on dealing with the problem of continuously monitoring the exposure from an overhead view for a very long time (i.e., several months). After designing and validating a measurement setup suitable for our objectives, we extensively collected 5G and pre-5G exposure data, followed by a detailed analysis using a Spectrum Analyzer from the proposed location i.e. University Hospital of Tor Vergata (Polyclinic). The results show that although the proportion of 5G exposure is generally lower than pre-5G, both in terms of field strength (up to 0.7 [V/m]) and in proportion w.r.t. other wireless technologies (typically less than 15%). Additionally, both the intensity and occurrence of 5G exposure peaks increase rapidly over the months, suggesting that 5G exposure levels will soon increase.

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Acknowledgement

Foremost, I would like to acknowledge my gratitude to my supervisor Dr. Luca Chiaraviglio who made this work possible. His guidance and advice carried me through all the stages of working and writing my project. I would also like to thank my committee members for letting my defense be an enjoyable moment, and for your brilliant comments and suggestions, thanks to you.

I am deeply grateful to my parents for their boundless love, appreciation including my brothers and friends for their continuous support throughout this journey. Your prayer for me was what sustained me so far.

Finally, I would like to thank God, for letting me through all the difficulties. I have experienced your guidance day by day. You are the one who let me finish my degree. I will keep on trusting you for my future.

Vishnu Sai Muppalla

INTRODUCTION

CHAPTER 1

1.1 Background study

The DEPLOYMENT of 5G networks is now an ongoing step in many countries around the world, including Italy. 5G is expected to become the dominant general-purpose technology (GPT) over the next decade, delivering a variety of services that will bring trillions of global economic results. However, the benefits of 5G are well understood and recognized - mainly in terms of improved throughput and latency, installing base stations that support 5G features is still a matter of controversy.

Unsurprisingly, the term “5G exposure” is causing a feeling of concern in part of the population, mainly because the electromagnetic fields (EMFs) emitted by 5G Next Generation-B nodes(gNB) are believed to be comparatively higher than those emitted by pre-5G technologies (e.g., 2G/3G/4G). While the technology has not yet reached its level of maturity (due to the early installation of millimetre wave antennas, for example), 5G is fast becoming an accessible wireless option, especially in urban areas.

In line with previous generations before 5G (2G/3G/4G), 5G requires the installation of new antennas in the area, which inherently contributes to the overall level of exposure emitted by cell towers. Monitoring the level of exposure from cellular networks is a complex problem in itself and is further complicated in the context of 5G [1]. The features of this technology include, for example, the ability to adjust the output power of antenna elements to several beams targeted at users who need to transmit data over a 5G connection.

1.2 Project Statement

In this context, measuring the impact from a live 5G network is fundamental to controlling 5G network deployment and its impact on EMF levels. On the one hand, we can better understand the impact of this technology in practical/realistic conditions, especially when new frequencies are introduced that are not necessarily used by pre-5G technologies (e.g. below 6 [GHz] and/or mmWave). The initial launch of 5G NR will build on existing 4G LTE infrastructure in Non-standalone (NSA) before standalone (SA) matures with a 5G core network.

In addition, a spectrum can be dynamically allocated between 4G LTE and 5G NR. Where 5G NR standalone (NSA) refers to a 5G NR deployment option that relies on the control plane of an existing 4G LTE network for control functions [Rf wireless, 2017]. In addition, the implementation of 5G networks with standalone capabilities (NSA) enables a high level of collaboration between 5G and 4G to provide cellular services, often using carrier aggregation functions spanning 4G and 5G bands. Last but not least, 5G (like 4G) does not consist of a single band, but rather can be delivered in a huge array of bands (e.g., sub GHz, mid-band, mm-Wave).

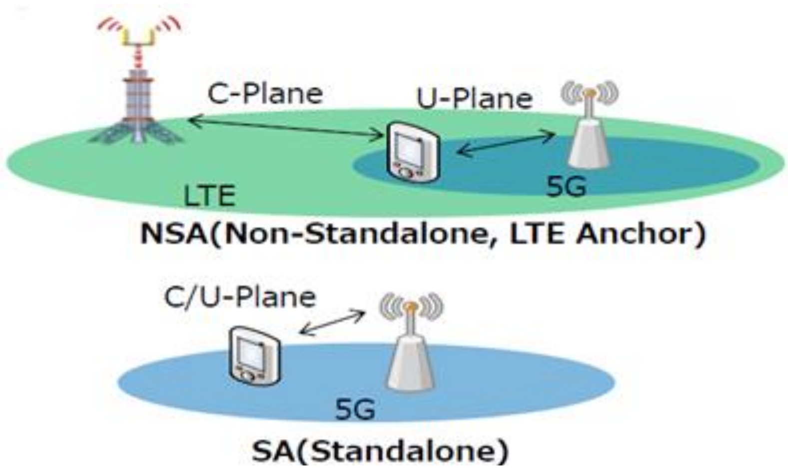

Figure 1: 5G NR NSA mode and SA mode[source:rfwireless]

While measuring EMF levels is critical during (and after) the installation of a new base station, running extensive campaigns using commercial 5G gNBs is challenging for a variety of reasons.

Recently, standards bodies such as the International Electrotechnical Commission have provided both methodologies and up-to-date data on the impact of commercial 5G deployments. More specifically, chountala et al. [2] performed electromagnetic field (EMF) measurements with a mobile lab, including tests with active traffic injected into the network, and concluded that the results show that without induced 5G traffic, EMF caused by 5G signals was negligible. With the increase in traffic, the EMF increased. The total EMF caused by all mobile services, including 5G, remained well below the norm at the test site.

Where EMF measurements based on an access point approach have been performed by Carciofi et al., [3] and the results show that an extensive measurement campaign was carried out in different scenarios and for different bands including ELF (extremely low frequency) fields; showed a good agreement between dynamic (driving tests) and static measurements. To compare static and dynamic measurements, two approaches to the proposed data analysis and data processing were adopted and compared, namely point-to-point and "Nearest-Point Processing (NPP) Chiaraviglio et al [4] have developed a new methodology for measuring 5G mass impact, including various instruments that are used in cascade, and concluded that the sight conditions and the distance from the 5G base station play a great role in determining the level of exposure. Where we do perform a thorough exposure assessment from a commercial 5G base station, again forcing traffic into the network. Broadband measurements including 5G signal, were conducted by Nedelcu et al. over a wide range of base stations. Wideband exposure data (including 5G) were also recorded.

1.3 Goal and Objective

This thesis is based on the need to study various research papers, so the natural question arises: why should we focus on one more work on measuring the 5G exposure? The answer is that while previous work has typically provided extensive area impact assessments, little effort has been made so far to understand and describe the evolution of massive 5G impact over a very long period (e.g., months/years). Monitoring the evolution of massive 5G exposure over a long period can not only allow long-term trends to be identified (capable of capturing, for example, the impact of the level of 5G adoption by users on impact) but also to understand the evolution of the 5G network itself, including the transition from NSA(Non-Standalone) to Standalone (SA), change bandwidth allocation policies between different operators and the introduction of new 5G bands [1].

Thus, this thesis aims to shed light on Massive long-term 5G exposure metrics. In particular, we compare the temporal evolution of 5G exposure with the pre-5G one, measured from a proposed single location over a period spanning three complete months. Specific contributions of our work include:

1) the design of measuring test equipment and measurement parameters for continuous and long-term monitoring over multiple bands by several operators hosted,

2) the analysis of massive long-term exposure trends,

3) Comparing the temporal evolution of the 5G exposure against the pre-5G one and evaluating its corresponding field strength.

THE JOURNEY FROM 1G TO 5G

CHAPTER 2

2.1 Literature Review

The process of creating next-generation technology begins many years before it can be commercialized, and 5G is no exception. The earliest stages of 5G can be traced back to 1948 when Bell Labs mathematician Dr Claude Shannon published a landmark paper on data storage and transmission. In it, he set a theoretical limit on the amount of information that could be transmitted on a given frequency. Perhaps, with the correct design of the signal and its calculations. In practice, the throughput of this network could be maximized [Qualcomm,2020].

Starting with 1G, which is the first generation of wireless mobile technology. These are analog mobile communication standards that were later replaced by 2G. The main difference between the two generations of mobile phones is that audio transmission on 1G networks was analog whereas 2G networks were all digital, the Nordic Mobile Telephone (NMT) and Advanced Mobile Phone System (AMPS) systems being the most widely used worldwide.

The transition to second-generation (2G) cellular networks is intended to improve analog solutions with circuit-switched digital solutions. which was launched based on the GSM (Global System for Mobile Communications) standards created by the European Telecommunication Standards Institute (ETSI) in Finland in 1991. 2G networks provide faster and more secure wireless communications. Voice transmissions were first encoded into digital signals before transmission over the network [14]. The most common 2G cellular systems, with the notable exception of IS-95, are based on TDMA, GSM, D-AMPS, PDC, iDEN, and PHS, where Time Division Multiple Access (TDMA) is a shared channel access method medium network. Where several users were allowed to share the same frequency channel by dividing the signal into different time slots.

The evolution of mobile networks

	1G	2G	3G	4G	5G
APPROXIMATE DEPLOYMENT DATE	1980s	1990s	2000s	2010s	2020s
THEORETICAL DOWNLOAD SPEED	2 Kbps	384 Kbps	56 Mbps	1 Gbps	10 Gbps
LATENCY	N/A	629 ms	212 ms	60-98 ms	< 1 ms

Source: techtarget,2021

3G:

3G is a third-generation wireless mobile communication technology, also referred to as a third-generation partner project. This is an upgrade from 2G, 2.5G, GPRS and 2.75G EDGE networks, which provide faster data transfer and better voice quality. This network was replaced by 4G and later by 5G. This network is based on a set of standards used for mobile devices and mobile communication services and networks that conform to the International Telecommunication Union-2000 (IMT-2000) specifications of the International Telecommunication Union. [14].

3G Branded Standards

1)The Universal Mobile Telecommunications System (UMTS) is a third-generation mobile cellular system for networks based on the GSM standard, UMTS is a component of the International Telecommunication Union IMT-2000 standard set where it uses wideband code-division multiple access (W-CDMA) radio access technology to offer greater spectral efficiency and bandwidth to mobile network operator can also transfer data at high rates and supports traditional cellular voice, text, and MMS services, allowing mobile operators can deploy higher bandwidth applications such as music-on-demand, TV and video streaming, and broadband Internet access[wiki,2016].

2)TD-SCDMA - Time Division-Synchronous Code Division Multiple Access (TD-SCDMA) is a 3G format used in China as an alternative to W-CDMA for the national standard of 3G mobile telecommunication [15].

3)CDMA2000 (also known as C2K or IMT Multi-Carrier (IMT-MC)) is a family of 3G mobile technology standards for sending voice, data, and signalling data between mobile phones and cell sites. Which was developed by 3GPP2 as a backwards-compatible successor to second-generation cdmaOne.

4G:

4G is the short name for fourth-generation wireless, also known as the Long-Term Evolution (LTE) standard (a 4G potential system). The stage of broadband mobile communication replaces 3G (third-generation wireless networks) and is the precursor to 5G (fifth-generation wireless networks). The 4G wireless cellular standard was defined by the International Telecommunication Union (ITU) and specifies key features of the standard, including transmission technology and data rates. Each generation of wireless cellular technology has introduced higher bandwidth speeds and network capacity. 4G users will get speeds of up to 100 Mbps, while 3G only promised a maximum speed of 14 Mbps [16].

At its most basic level, a 4G connection works through an antenna that transmits radio frequencies, allowing mobile devices to connect to mobile networks. 4G was first defined by the ITU in 2008, but its speeds and specifications were not immediately available to mobile devices. networks or mobile devices. As a temporary step towards 3G, LTE provides more bandwidth than 3G without reaching the full network speed of at least 100 Mbps that 4G promises. 4G is also an IP (Internet Protocol) based standard for both voice and data, unlike 3G which uses IP for data only and allows voice to be carried over a circuit-switched network.

4G is also an all-IP (Internet Protocol) based standard for both voice and data, unlike 3G which uses IP only for data and allows voice over a circuit-switched network. Being an all-IP network, 4G is more efficient for mobile operators in terms of operation and optimization than managing different network technologies for voice and data.

4G transmission and reception capabilities are based on MIMO (Multiple Input Multiple Output) and Orthogonal Frequency Division Multiplexing (OFDM) technologies. Both MIMO and OFDM allow for more throughput bandwidth compared to 3G. OFDM provides higher speeds than the primary technologies underlying 3G, which include Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). With MIMO, 4G reduces network congestion compared to 3G because it can support more users.

5G:

The fifth Generation(5G) is the next generation of radio systems and network architecture that delivers extreme broadband, ultra-robust, low latency connectivity, and massive networking for the Internet of Things [future networks,ieee]. It does not merely represent the next step from 4G, but a dramatic paradigm shift in wireless communication. As revolutionary as 4G was providing a new platform for innovation by making apps that relied on high-speed data possible, with a similar set of technical requirements across the board [16]. 5g, on the other hand, will serve all sorts of users where It offers the promise of increased bandwidth with peak speeds as high as 20 Gbps, which is dramatically more than the 100 Mbps specified by 4G[Sean,2021].

Even though previous generations of mobile technology (such as 4G LTE) focused on guaranteeing connectivity, 5G takes connectivity to the next level by providing clients and subscribers with connected experiences via the cloud [14]. Without user involvement or the need to reauthenticate, mobile users can stay connected as they travel between outside wireless connections and wireless networks inside buildings [17]. With ultra-high-speed data transfer (which is about 1GB per second plus), which is significantly faster than the speed of existing LTE networks, 5G networks can connect a huge number of devices, i.e., about 10-100 times more. the number of simultaneous mobile connections with ultra-low latency [11]. Furthermore, 5G networks are more efficient (i.e., they last longer) and have 5 times lower

latency than LTE networks [12].

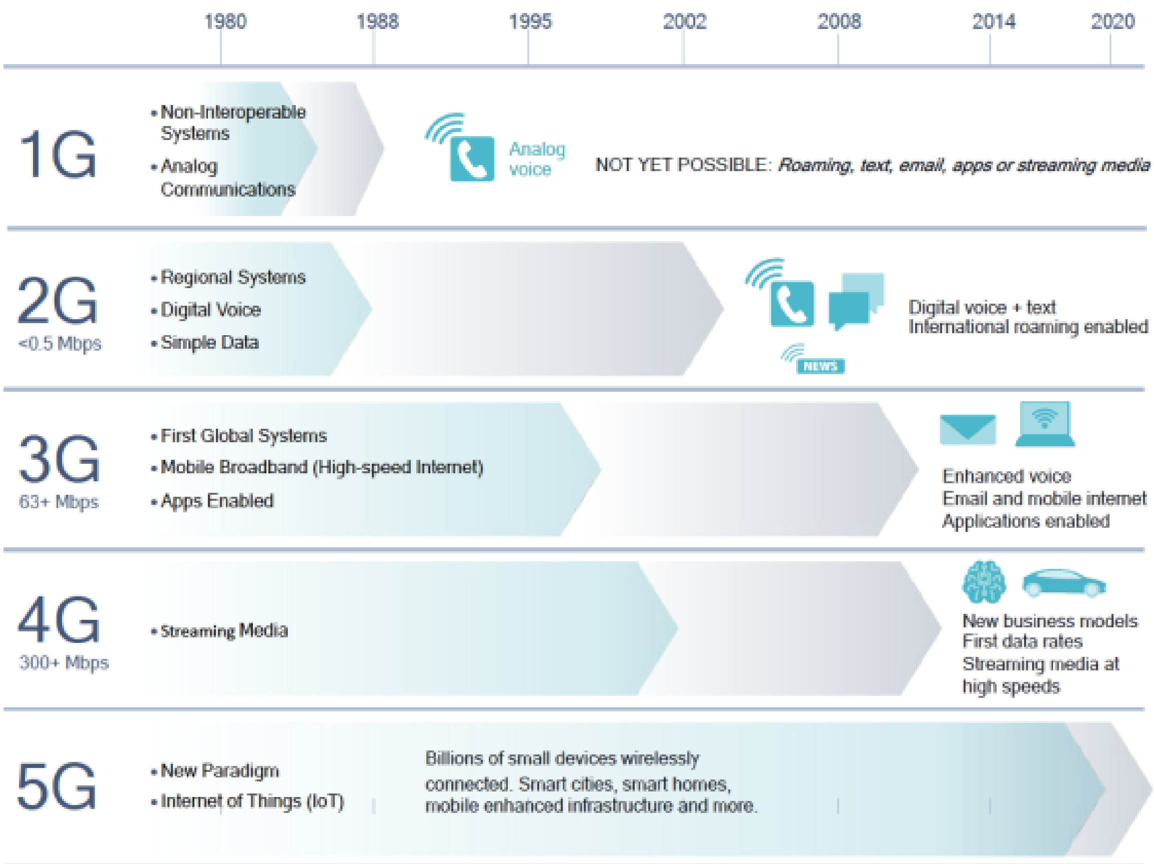

Figure 2: Mobile network Evolution over two decades [source: Qualcomm,2020]

2.2 General Characteristics of 5G vs. 4G

First,5G is designed to increase spectrum efficiency compared to previous generations. This means that less bandwidth and less power are needed to transmit a certain amount of information. 5G also uses only a very small fraction of the transmission power for non-data signalling and uses advanced antenna technology to direct power where it is needed and uses new features (e.g., previous generations to a limited extent. Second, new parts of the spectrum are reserved for the 5G signal and in some cases, new spectrum allocation techniques (e.g. Dynamic Spectrum Sharing (DSS)) are adopted to share 4G bandwidth for both 4G and 5G signals. Third, the use of high frequencies (even below 6 [GHz]) suggests that propagation effects (e.g. due to different viewing conditions and/or different distances from the serving gNB) have a large impact on the exposure levels. As a result, the exposure generated by the 5G gNB strongly depends on the specific location where the EMF is assessed.

While 4G only uses frequencies below 6 GHz, NR (New Radio) supports two bandwidths: Frequency Range 1 (FR1), commonly referred to as sub-6 GHz, which ranges from 450 MHz to 7125 GHz, and Frequency Range 2 (FR2), commonly referred to as millimetre wave, which ranges from 24 GHz to up to 50 GHz. Where the maximum bandwidth in FR1 is in the range of 100 MHz, while the maximum bandwidth in FR2 is 400 MHz. These values are much larger compared to LTE bandwidth, which is limited to 20 MHz. Both 4G and 5G use Orthogonal Frequency Division Multiplexing (OFDM). However, while in LTE the subcarrier spacing is fixed at 15 kHz, NR introduces flexible numerology to allow the use of variable subcarrier spacing. In particular, the subcarrier spacing can be chosen equal to $2\mu \cdot 15$ kHz, where $\mu = 0, 1, 2, 3, 4.$, is increased by a factor of 2μ from the LTE subcarrier space. The Modulation schemes are similar to LTE and include binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16th-order quadrature amplitude modulation (16

QAM), 64 QAM and 256 QAM. The time duration of both LTE and NR frames is equal to 10 ms and consists of 10 sub-frames, each of which has a time duration of 1 ms. However, in NR, different numerologies provide a different number of OFDM symbols per subframe. Accordingly, in NR, a subframe is divided into a 2µ slot of 14 OFDM symbols (12 symbols for the extended cyclic prefix) [5].

Table 1: Key differences between 4G and 5G [source: ITU,2020]

DIFFERENCES 4G / 5G

Feature	4G	5G
Antenna pattern	Fixed, equal for signalling and all data	**Beam forming**
Typ. beam pattern	Azimut: 60° or 360° Elevation: ≈ 10°	Depending on type of signal and antenna
Frequency range	400 MHz to 6 GHz	FR1: 400 MHz to 7 GHz, FR2: 28 GHz, 38 GHz, (43, 47, beyond)
RF bandwidth	≤ 20 MHz	≤ 100 MHz (FR1), ≤ 400 MHz (FR2)
Signalling	In mid of frequency band, always on, same pattern as data	At fixed frequencies, not necessarily in same band, beam constant or scanning
Reference symbols	Cell specific, always tranmitted, distributed over the bandwidth	Flexible and configurable reference signal concept. Only SSB is “always on“

We can see Key differences that are highlighted in the above Tab. 1 whereas, in LTE and 5G, the smallest physical resource is a Resource Element (RE), given by one frequency domain subcarrier and one OFDM symbol. In NR, RE is mapped in frequency-time differently, according to accepted numerology. An NR Resource Block (RB) consists of 12 consecutive sub-carriers in the frequency domain. Finally, the Resource Grid (RG) is a representation of the available Resource Elements for the available subcarriers and symbols.

Like all radio communications, including radio and television broadcasting, satellite communications, and previous generations of mobile networks, 5G uses radio waves to transmit information between base stations and connected devices. Radio waves are a form of electromagnetic field that is transmitted and received by antennas. It belongs to the radio frequency part of the electromagnetic spectrum, as shown in Figure 3. 5G uses frequency bands allocated by regulators ranging from 600 MHz to 40 GHz, which are at or near the ranges already used by previous generations of mobile networks, satellite communications and other radio applications. Radio waves, including the new higher bands used by 5G, called millimetre waves, are very different from electromagnetic fields at the top of the spectrum, called ionizing radiation, with frequencies more than 100,000 times higher than the radio waves used for communications. Ionizing radiation is known to have high enough frequencies (and photon energy) to break chemical bonds, which can cause tissue damage. Radio waves do not have such properties.

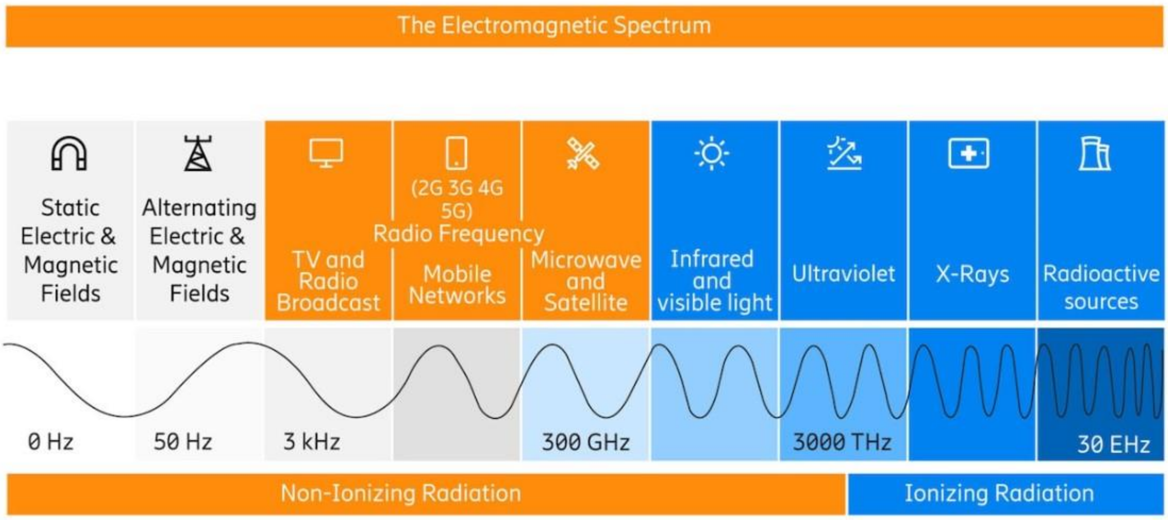

Figure 3: The electromagnetic spectrum. [Ericsson website,2021]

2.3 5G EMF Exposure

EMF exposure assessment methods for time-varying mobile telecommunications signals have relied on the measurement and subsequent extrapolation of user-independent signals that are transmitted continuously (or periodically) at constant power, independent of traffic load. These signals differ from one telecommunication technology to another (Table 2): i.e., the broadcast control channel (BCCH) for GSM, common pilot channel (CPICH) for UMTS and cell-specific reference signal (CRS), and synchronization signals. (SS) and Physical Broadcast Channel (PBCH) for LTE. In the case of NR, there is no CRS, but the "always on" signal components are, as in LTE, the primary and secondary synchronization signals (PSS and SSS) and PBCH. PSS and SSS use user equipment to find, identify and synchronize with the network, while PBCH contains a minimal amount of system information. Together, these signals form an SS/PBCH block (also referred to as an SS or SSB block) [6].

Table 2: Constant-Power Signal Components of Second Through Fifth Generation Telecommunications Technologies

(Generation) Technology	Constant-power component(s)
(2G) GSM	BCCH (Broadcast Control Channel)
(3G) UMTS/CDMA	CPICH (Common Pilot Channel)
(4G) LTE	CRS (Cell-specific Reference Signals), a primary synchronization signal (PSS) and secondary synchronization signal(SSS), and a physical broadcast channel(PBCH)
(5G) NR	PSS, SSS, and PBCH (i.e., ‘SS/PBCH block’ or ‘SS block’)

Based on decades of scientific research, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) have issued guidelines for limiting human exposure to electromagnetic fields (EMF). These guidelines formed the basis of recommendations from internationally recognized institutions such as the World Health Organization (WHO), the US Federal Communications Commission (FCC) and the International Telecommunication Union (ITU), as well as recommendations from the European Council. However, some countries or regions (e.g., Brussels, Belgium) have adopted their own stricter legislation that may delay or even prevent the deployment of 5G networks due to EMF saturation where the current pre-5G limit levels have already been reached to the telecommunication infrastructure [6].

2.4 Impact of 5G Features on EMF

The influence of 5G technologies on EMF levels remains unclear, despite numerous dedicated studies. 5G will be characterized by a set of radical new technologies. In this section, we aim to analyze the main ones in terms of relevance and expectations impact on EMF exposure levels compared to currently deployed cellular networks. The analysis developed is not comprehensive and needs to be supported and verified through extensive EMF measurement campaigns.

Tab. 3 summarizes each function of 5G technology as well as its significance in terms of EMFs. One of these goals is the use of massive MIMO antenna arrays recognized by 5G features. This in turn means an increased number of antenna's radiant power at each location. While some recent works suggest that this 5G functionality will have a positive impact on EMF exposure levels, the rationale cannot be generalized [7]. The effect of MIMO is highly dependent on configurations chosen and approaches taken to measure EMF levels [N. Perentos et al,2012]. Consequently, the academic and industrial community must assess soon MIMO's potential gain in terms of EMF levels.

Beamforming is another recognized feature of 5G. It enables spatially selective communication as the radiated power is concentrated in narrow and selected spatial directions. As a result, beamforming is believed to result in an overall reduction in EMF exposure levels compared to the current deployed Base Stations.

However, due to the concentration of power in the selected directions, there may be an increase in the EMF levels in the area of the territory corresponding to these directions. Similarly, the use of millimeter wave bands for directional communications in 5G networks can be beneficial for EMF exposure levels. Millimeter wave communications are characterized by higher path losses than modern microwave communications. Therefore, the received EMF may be lower compared to that generated by currently deployed BSs. In this context, it is worth mentioning that 5G is expected to use various coexisting cell layers with a dense deployment of small cells similarly, the exploitation in 5G networks of mm-Wave bands for directional communications may be beneficial for the EMF exposure levels. mm-Wave communications are characterized by higher path losses compared to current microwave communications.

Therefore, EMF exposure levels are expected to be reduced compared to currently deployed BSs due to shorter distances from the BS to the user. However, a possible increase in EMF levels in the vicinity of a small cell may also be observed compared to the current deployment. It is expected that the reduction in EMF promised by the use of small cells will be further enhanced by the adoption of offload mechanisms provided by the inevitable coverage overlap between different cell levels. In fact, according to such mechanisms, the power emitted from the most loaded cells could be reduced by offloading the users to other cells located in their vicinity.

Other key 5G technologies envisioned to decrease the EMF exposure levels are softwarization and Mobile Edge Computing (MEC). Specifically, on one hand with the softwarization, since different network functionalities, including most of the BS functionalities, will be realized at the software level, it will be possible that multiple operators will share the same BS hardware. As a consequence, the number of antennas radiating power and installed in the same site will decrease in the case in which each operator installs its physical equipment in the shared site. On the other hand, with the MEC, cloud computing capabilities will be enabled at the edge of the network. By properly managing the content stored in the MEC platforms, it may be possible to decrease the amount of transferred data, thus decreasing the radiated power. However, this vision will be affected also by the type of service provided by MEC, which may include high data rate services such as augmented reality. Similarly, the adoption of the Device-to-Device (D2D) paradigm in 5G networks is envisioned as a way to decrease EMF exposure levels.

Table 3: Influence of the 5G Technology Features on the EMF levels [Chiaraviglio et al.,2018]

Feature	Relevance to EMFs	Expected EMF Increase/Decrease
MIMO	Increased number of antennas radiating power. Impact of computing the radiated power when assessing the compliance with EMF limits.	-/+ The impact on the EMFs levels depends on the specific MIMO configuration and on the adopted approach for measuring the EMF levels.
Beamforming	Directionality control of the radiated power. Power concentrated into selected locations.	- General decrease w.r.t. currently deployed BSs. + Increase in selected locations.
mmWave	Path loss increase of radiated signals on mmWave bands.	- (Possible) decrease w.r.t. BSs exploiting micro-waves.
Small Cells	Installation of additional sources of power. Less power required to macro cells.	- (Possible) decrease w.r.t. the current cellular network. + (Possible) increase in proximity to the small cells.
Offloading	(Possible) reduction of radiated power from the most loaded cells.	- (Possible) decrease w.r.t. the current cellular network.
Softwarization	Sharing of the hardware infrastructure by multiple operators. Less antennas installed in the shared sites.	- Large decrease w.r.t. the case in which each operator installs its own physical equipment in the same site.
MEC	(Possible) decrease in the amount of transferred data in the air, thus decreasing the radiated power.	- (Possible) decrease w.r.t. to the current MEC-unaware network.
D2D	Reduction of tha amount of data transferred (and consequently of power) between the BS and the UE.	- Decrease w.r.t. current deployments exploiting classical communication schemes (e.g., UE to BS).
Sleep mode	BSs put in sleep mode radiate zero (or very low) power. The BSs that remain powered on may have to increase their coverage area.	- Decrease in proximity to the BSs put in sleep mode. + (Possible) increase in proximity to the BSs that remain powered on.
2G/3G Dismission	Reduction of the current EMF saturation levels in urban zones.	- Large decrease w.r.t the case in which all the legacy technologies are maintained.

In fact, with D2D a decrease in the amount of information exchanged between the UE and the BS will be expected. This in turn will reduce the number of EMFs generated by the BS. In the same direction, advanced power-saving techniques, including deep Sleep Modes (SMs), may be exploited in 5G networks.

Specifically, SM-based techniques may reduce the amount of EMF exposure levels since the BS that is not used is completely switched off (or in a low-power state). However, there could be an increase in the EMF levels in proximity to the BSs that remain powered on and have to increase their coverage also to the zones previously served by the BSs currently in SM. Finally, with the deployment of 5G networks, legacy 2G and 3G networks will be dismissed. This will positively impact the EMF exposure levels, especially in terms of the reduction of the current EMF saturation levels in urban environments.

The advantages and the disadvantages in terms of EMF exposure levels forecasted for the described 5G technologies need to be assessed against the aggregate radiation generated by the different BS layers operating with different access technologies, especially if legacy pre-5G networks already showed levels of EMF saturation, as revealed by some case studies. Moreover, they need to be assessed against the dependence of the EMF exposure levels on several factors, including e.g., the type of BS/UE, the BS/UE location to the user, and the location of the user [8].

2.5 Overview of EMF Exposure limits

The World Health Organization (WHO) and ITU have endorsed ICNIRP to develop the international EMF exposure guidelines, which have been mainly derived from the observation of thermal effects induced by EMFs on the body [9]. The observed effects include induced current and heating (for frequencies until 300 MHz), body heating (for the frequencies between 300 MHz and tens of GHz) and skin heating (for the frequencies above tens of GHz). 5G is expected to operate on all the aforementioned bands: (i) below 1 GHz to provide coverage in rural, suburban and urban scenarios (including for Internet of Things devices), (ii) between 1 and 6 GHz to offer a mixture of coverage and capacity, and (iii) above 6 GHz to grant very high data rates [5G PPP. EU website.,2017]

From a health perspective, there is a growing concern from the society that an indiscriminate increase in the number of antennas increases cancer cases – especially in the brain. Different independent studies have tried to shed light on this issue [10]. In this scenario, the WHO has classified high-frequency EMF fields as possibly carcinogenic to humans based on the possible increased risk of glioma, a malignant type of brain cancer associated with the use of cordless phones. The WHO has pointed out that there may be a risk, and that further research, especially on the long-term effects, is needed. In any case, if the EMF fields are preserved below ICNIRP limits no adverse effect should occur for public health.

In general, RF-EMF limits applicable to base stations are usually expressed as power density (unit W/m^2) or electric field strength levels (unit V/m). Figure 4 below shows the power density limits for the public that are prescribed in many countries around the world (from the ICNIRP 1998 guidelines). These so-called reference levels are frequency dependent, but from 2 GHz to 300 GHz they are defined at a constant level of 10 W/m^2 (or 61 V/m expressed as electric field strength). Importantly, they are also associated with an average time, such as 6 or 30 minutes, meaning that it is the average power density over the specified time that is to be compared to the limit. Currently, the revision of ICNIRP limits is in progress.

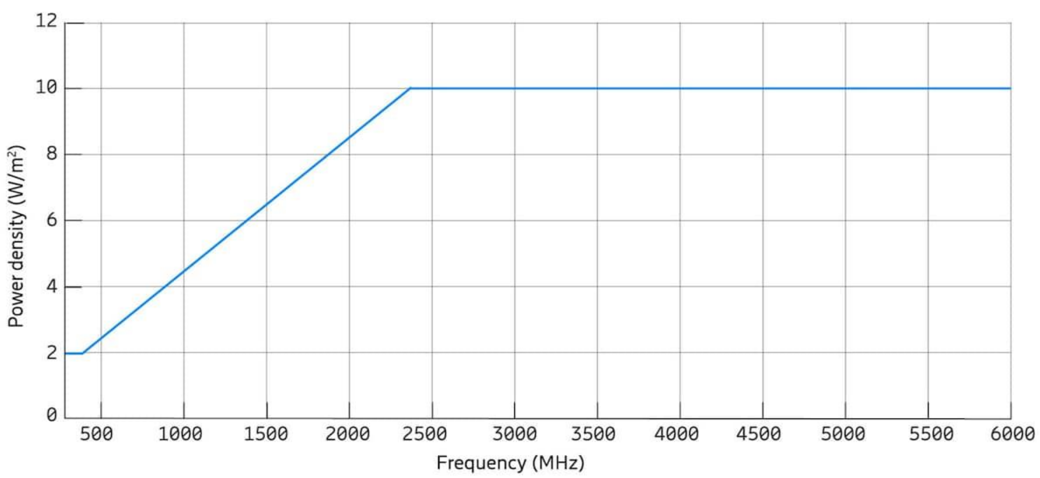

Figure 4: ICNIRP (1998) RF EMF limits (reference level) for the general public in the frequency ranging from 300MHZ to 6GHZ expressed as power density. [Ericsson website,2021]

EXPERIMENTAL SETUP

CHAPTER 3

3.1 Tools and Software

The long-term measurement activity setup used for this study is defined by the following requirements:

I. Performing narrow-band measurements over various bands for several operators,
II. Define the set of monitored bands based on the ones effectively deployed in the territory,
III. Storing the corresponding timestamp for each measured data,
IV. Access to the timestamp and measured data at a low speed but in parallel with monitoring activity,
V. Characterize the timestamp-plus-measured-data based on the traffic on specific days.

Based on the previous constraints, our setup includes a blend of hardware and software capabilities.

Hardware: Concentrating on hardware, we use the Anritsu Remote Spectrum Monitor MS27102A, which enables continuous real-time monitoring of the radio spectrum in the 9kHz - 6 GHz frequency range [1]. It is a full-featured platform for monitoring and recording signals at user-specified frequencies and is capable of speeds up to 24 GHz/s, allowing this probe to capture many types of signals including periodic or transient transmissions as well as short bursts of signals. The instantaneous 20 [MHz] FFT bandwidth available on the MS27102A remote spectral monitor provides the ability to capture broadband signal activity in real time for subsequent post-processing. The set of metrics that can be measured/extracted by SA is huge, ranging from the temporal evolution of the spectrum over time (i.e. spectrogram), both in RT through a maximum BW equal to 100 [MHz] and not in reality. time over a wider BW, to the total power received over the 5G channel, where IQ can be captured both in block mode and streamed. The MS27102A remote spectrum monitor is offered in an IP67 weatherproof enclosure for outdoor mounting in the harshest environments and comes standard with one RF input, although a second port can be optionally added for dual antenna use. Anritsu provides a user manual that lists all SCPI commands, a description of the commands, and the correct syntax required for each command. Additionally, each pair of IQ monitor data outputs is time-stamped using high-precision GPS signals. This allows the user to use IQ data for Time Distance of Arrival (TDOA) applications to geolocate signal positions. The timestamp resolution of the IQ data is less than 9 ns for accurate signal position calculations.

Software: With a focus on software, we use Search24 software - a patented ARPA Lazio application (following national and international measurement procedures) to remotely control non-vector spectrum analyzers. In detail, a "save on event" function is also available to capture spectrum measurements only when certain user-specified thresholds are exceeded, saving memory space as only the signals of interest are captured and recorded. The Search24 software integrates the measurement algorithms as a series of Standard Commands for Programmable Instrument (SCPI) commands that are exchanged between the Search24 general-purpose computer and the MS27102A monitor over a private Ethernet LAN. The Search24 software allows for a high level of measurement personalization, including setting various characteristics for each monitored band such as Span, Integration Bandwidth, Number of Samples, Resolution Bandwidth (RBW) and Video Bandwidth (VBW).

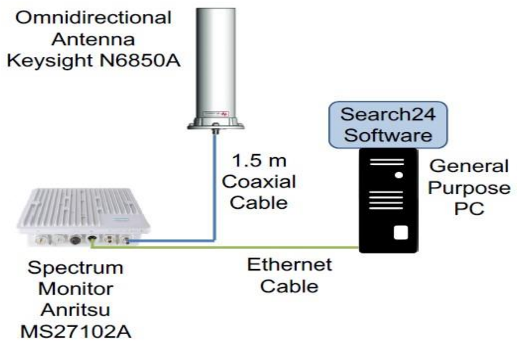

Figure 5: Outline of monitoring setup. [Chiaraviglio et al,2022]

Here Fig. 5 shows a scheme of the considered measurement chain. In addition to the already mentioned monitoring unit and Search24 software, the chain also includes a receiving (passive) antenna with the leading characteristics, which is adapted for omnidirectional sites.

Passive antenna

Today's complex antenna systems, including managing a complex mix of multiple standards, bands and layers at the same radio site, place high demands on the ability to create solutions with stable performance. Using our preferred antenna that supports communication interoperability and an easy plug-and-play solution. We prefer to use passive antennas because they have no gain stages. With these smart devices, operators can maximize the efficiency of their valuable spectrum resources and increase network capacity. With their key advantage such as Time Division Duplex Beamforming (TDD) which is adaptive beamforming with maximum performance, and low site reliance.

In our case, we use an omnidirectional antenna, capable of covering all frequencies from mobile networks to the mid-band of 5G. Where an omnidirectional antenna is typically characterized by lower gain values compared to directional antennas, although they have high accuracy and gain, resulting in constructive interference. Then the receiving antenna is then connected to the control unit with a short coaxial cable (which introduces practically insignificant losses in the measuring chain) [1]. To maximize the amount of exposure captured. If the purpose of the measurement is to test exposure against maximum limits, a different antenna (ie typically triaxial and dual polarization) must be used using the directional antenna used to verify radio coverage. as well as the qualitative EMF values associated with the use of massive Multiple-Input Multiple-Output in 5G) [4] beamforming techniques and small cell network topologies, facilitating the IMT2020 vision for improved mobile broadband, ultra-reliable low-latency communications, and massive Machine Type - but our work is not focused on this theme.

3.2 Base Station and Measurement Location

In the next step, we select the target monitored base station and the measurement location. Based on the first, we select and identify a cell site in the neighbourhood of the University of Rome Tor Vergata building shown in Fig. 6(a). The site is hosted by multiple operators with different technologies. Which is close to our measuring point of the University Hospital (Polyclinic). For a fair comparison, this work focuses on the Italian network operators, namely W3, TIM, Vodafone, Linkem and Iliad, and their respective web-hosted antennas, which include both pre-5G and 5G technologies, at the moment Linkem currently operates only pre-5G. In this way, we monitor the exposure generated over the territory by several operators.

Focusing on the measurement site, we select the Line-Of-Sight (LOS) position on the 2nd floor of the University Hospital, shown in Fig. 6(b). Fig. 6(c) highlights the aerial view of the measurement location. The location is located at a distance of approx. 580 [m] from the serving base station, inside the main lobes of all sectors facing the University Hospital (Polyclinic) and in a zone where the traffic requirements are not negligible (due to the presence of patients and hospital employees). In addition, the zone includes student residences and heavily loaded streets and university campuses, so we expect significant traffic even during non-working hours (e.g., late evenings, weekends, and public holidays). Finally, the choice of the LOS position guarantees good propagation conditions at the measurement location and thus (possible) good signal levels of the technology as a whole.

To deal with the mentioned aspects, we obtain a set of measurement targets. First, the measurement must be selective, which means we need to separate exposure contributions from different technologies, with a particular focus on 5G and pre-5G. Secondly, the measurement must be comprehensive, which means that in addition to individual contributions, we must be able to measure the overall exposure at a particular proposed location in order to evaluate it from time to time. Thirdly, the measurement must be reliable, which means that we must be able to limit the occurrence of errors that can invalidate the results. Fourth, the measurements must be explicable, meaning that similar metrics measured by different instruments must follow each other, or in the case of variances, plausible explanations for the observed

a) Cellular site for multiple operators hosting both pre-5G, and 5G base stations

b) Internal view

c) Antenna View

Figure 6: cellular site, internal and antenna view of the location.

3.3 Measurement Parameters

We then shifted our attention by providing the input parameters as required by the Search24 software. Focusing on the monitored bands, we start to perform a preliminary scan with a portable spectrum analyzer (equipped with demodulation capabilities) to determine the technologies and frequencies of multiple operators (W3, TIM, Linkem, Vodafone, Iliad) that are found at the measurement location Tab. 4 will report the results of our Initial analysis. Apart from using a wide set of frequencies to support both pre-5G and 5G services, the base station consisting of multiple operators provides 5G connectivity over six different portions of bandwidth belonging to their mid-band frequencies. However, the W3 operator has originally licensed three portions at 3447.5 [MHz] and 3547.5 [MHz],3610[MHz] are licensed for 5G mobile service. Whereas coming to other operators while Iliad is licensed with 3630 [MHz], Vodafone with 3680 [MHz], and TIM with 3760 [MHz] are licensed with one portion each. However, such information is sufficient to confirm our intuition (derived from real measurements): the W3, Iliad, TIM, Vodafone and Linkem operators are providing 5G with their equipment, by exploiting their licensed band in the mid-band range.

Table 4: MID BAND FREQUENCIES USED BY MULTIPLE OPERATORS OVER THE MEASUREMENT LOCATION

Operator	Center Frequency [MHz]	Bandwidth [MHz]	Technology
W3	796	10	pre-5G
Tim	806		
Vodafone	816		
Tim	935		
Vodafone	945		
W3	955		
Iliad	1835	20	
W3	1850		
Vodafone	1870		
W3	2120		
Tim	2137.5		
Iliad	2150		
Vodafone	2162.5		
W3	2585		
Iliad	2635		
Vodafone	2647.5		
Tim	2662.5		
W3	2680		
Linkem	3468.5		
Linkem	3568.5		
Linkem	3589.5		
W3	3447.5		5G
W3	3547.5		
W3	3610		
Iliad	3630		
Vodafone	3680		
Tim	3760		

We then set the parameters for each bandwidth shown in Table 4. In more detail, To differentiate between different telecommunication signals (2G–5G), the Resolution bandwidth (RBW) is defined as the entire signal bandwidth (or in the case of hardware limitations, the largest resolution bandwidth (RBW) allowed by the instrument); and the Video signal bandwidth (VBW) of the monitoring unit is set according to the standard settings. We then allow the SA automatically, resulting in RBW = 100 [kHz] and VBW = 300 [kHz], respectively. Eventually, we adopt a “Peak” type detector and a “Max Hold” measurement type [1]. In this way, the peak of received power for each frequency sample is stored (during the measurement window), and the maximum value over time for each frequency is saved. The unit range is set to the bandwidth values in Tab. 4, with an additional 1 MHz guard band on each side. The channel power which is the average power of the pre-5G and 5G technologies is calculated in the time domain in the measurement interval and then calculated by integrating over the exact bandwidth values of Tab. 5, based on a Root Mean Square (RMS) trace detector, a rolling average type detector which calculates and analyses data points by creating a series of averages of different subsets of the full data set here using 200 samples for computing the average. Ultimately, the number of sweep points is set equal to the maximum one allowed by the unit (i.e., approx. 501 per band).

Table 5: PARAMETERS SETTINGS FOR EACH BAND. [Chiaraviglio et al,2022]

Parameter	Value
RBW [kHz]	100
VBW [kHz]	300
Span [MHz]	Bandwidth + 2 MHz
Chanel Power Range [MHz]	Bandwidth
Trace Detector	RMS
Type Detector	Rolling Avg.
The number of avg. samples	200
Sweep points	501

Finally, after Search24 with the required parameters as the input from Tab. 4-5. The idea of the software is quite simple: each band is scanned sequentially (starting from lower frequencies up to higher ones). For each band, the channel power measurement is retrieved at the end of the observation period equal to 10 [s], to ensure that the considered monitored signal under consideration is stabilized. In addition, Search24 adds the current timestamp to the measured channel power. The entire loop over all the multiple operators with their respective bands ends in less than 2 minutes for each of the operators, which is then continuously repeated from time to time.

EXPOSURE ANALYSIS

CHAPTER 4

4.1 Exposure Analytics

We have recorded measurements from the proposed location of the University Hospital (Polyclinic) of TorVergata covering a span of three whole months between late May 2022 and late August 2022. After extracting the data measurements from the setup at the location we start to analyze the recorded time-exposure data, and then we perform a post-processing step of data analytics to extract the useful information to perform simulations by using the MathWorks software MATLAB.

In more detail, coming to our experiment by adapting an integrating approach we focus on each band and each hour per day in the considered 3-month period, where we run the following steps to compute the instantaneous Electric field [V/m] for each hour in the time domain:

- Step 1 Initially, we select samples that come under the current hour from the recorded data,
- Step 2 Then we clean the selected data by removing unnecessary and not-correctly measured data such as “NaN” values,
- Step 3 where an SA setup measures the received power P (dBm) of a signal,
- Step 4 Conversion of the received power samples from dBm to linear,
- Step 5 We then compute hourly average power from the samples in the previous step in that specific hour,
- Step 6 Conversion of the computed hourly time-averaged power, measured during a certain time from linear to dBm,

- Step 7 Finally We determine the instantaneous hourly Electric field E in V/m.
- Step 8 We then perform Operator Analysis specifically to study the pre-5G vs 5G trend behaviour based on day/night, weekend/weekday, and holidays/workdays periodicity.

Focusing on step no:7, the field level E [V/m] is expressed as mentioned formula:

$$E = \sqrt{\frac{Z \times 10^{(P-30)/10}}{A}} \quad (1)$$

With the Knowledge of the input received power to the base station **P [dBm]**, the antenna gain **G (direction-dependent) =**$\left(\frac{9.73}{\lambda \times 10^{AF/20}}\right)^2$, the impedance of free space **Z = 377[Ω], AF** be the antenna factor(dB/m) of the receiving antenna for the central frequency f in [Hz] of the current band, wavelength $\lambda = d/f$, and speed of light d = 299792458[m/s].

It is important to note that, with these settings, the measured power levels provide only an indication of the peak values (typically a large overestimate due to the effect of modulation).

Given the computed hourly electric field value for each band, we then compute the total electric field for the pre-5G and 5G technologies by summing them quadratically, to capture the total electric-field level, all three orthogonal components (X, Y, and Z) of the electric-field vectors are to be measured given the frequency of technology assignment of the site (reported in Tab. 4). Only, the electric field for each technology option is computed as the root sum square of the exposure values for the different frequencies.

4.2 Results

After performing all the measurements through our integrated approach, primarily we focus on the total 5G exposure vs. the pre-5G one vs time as shown in Fig 6. Several considerations after analyzing the figure. In the beginning, 5G exposure generally represents a minute portion of the pre-5Gone. Later it can be seen that pre-5G exposure exhibits a strong day/night and weekday/weekend comparatively to the 5G ones. However, In detail, it can be noted that 5G exposure is fluctuating and is high during the working days at Certain hours whereas the pre-5G exposure is low during the weekends, while peaks are concentrated at the central hours on working days. The observed behaviour is expected as the exposure is experiencing a huge amount of traffic due to the number of active connections in the area covered by the base station. Where it peaks generally located when most of the staff at the hospital, and students are at the University. On the other hand, the contribution from connections exploiting 5G is quite low, hence exposure trend of 5G is flat and smaller close to the minimum level when compared to pre-5G. As a third result, it is evident that 5G exposure shows different peaks that are concentrated occasionally both during working days and weekends.

Fourth, both intensities of 5G exposure and the frequency of the peaks are increasing with time, which demonstrates that 5G usage is exponentially increasing. Coming to the fifth observation, initially pre-5G exposure shows a drop (from late May 2022 until mid of June 2022) apart from the holiday i.e. on June 2nd, followed by a sudden rise (from mid of June until the end of July 2022), and then by a decreasing one again (at the beginning of August) followed by an increase at the end of August.

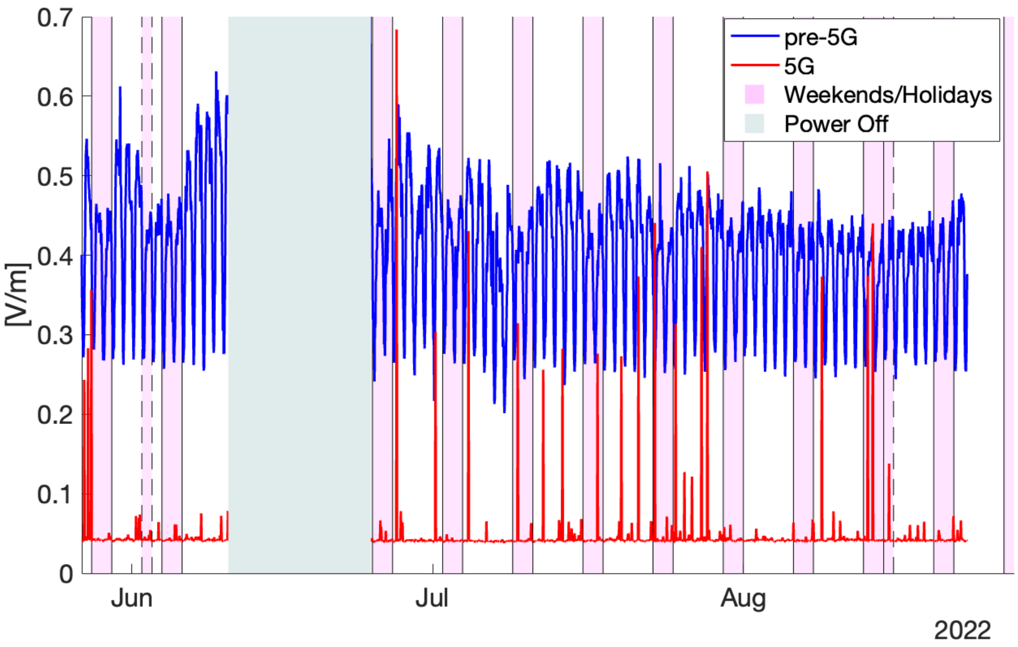

Figure 6: 5G and pre-5G exposure vs. time.

This behaviour can be explained by the below-mentioned reasons:

I. The number of incoming patients due to the outbreak of the pandemic disease, which forced many patients to get admitted as well as the number of hospital staff working continuously (including Doctors, nursing, and administration staff).

II. Due to an increase in the number of students and teaching faculty as well at the University located in the proximity of the measuring location because of the exam session held in the present from June till the end of July 2022.

III. There is a fall in the graph initially in August 2022 due to the summer holidays when most people are on the vacation.

IV. Due to the summer exam session, where most of the faculty and students are present at the University, there is a slight increase in the figure at the end.

Operator wise Analysis

Due to the presence of multiple operators, we then focus our study on the behaviour of total 5G vs pre-5G to evaluate each operator wise (includes Tim, Vodafone, Linkem, W3, Iliad) and note their exposure in the aforementioned time frame.

From the below-mentioned figures in Fig.7, it is evident that the evolution of 5G exposure through a period is constantly growing. Focusing our attention on Tim and Vodafone it can be seen that pre-5G exposure shares a major component compared to 5G exposure which is nearly small and shows a peak during certain time intervals in August 2022. While on the other hand, W3 and Iliad share a similar amount of 5G exposure and pre-5G at some instants of time. Coming to Linkem it is observed that only varying pre-5G exposure is measured.

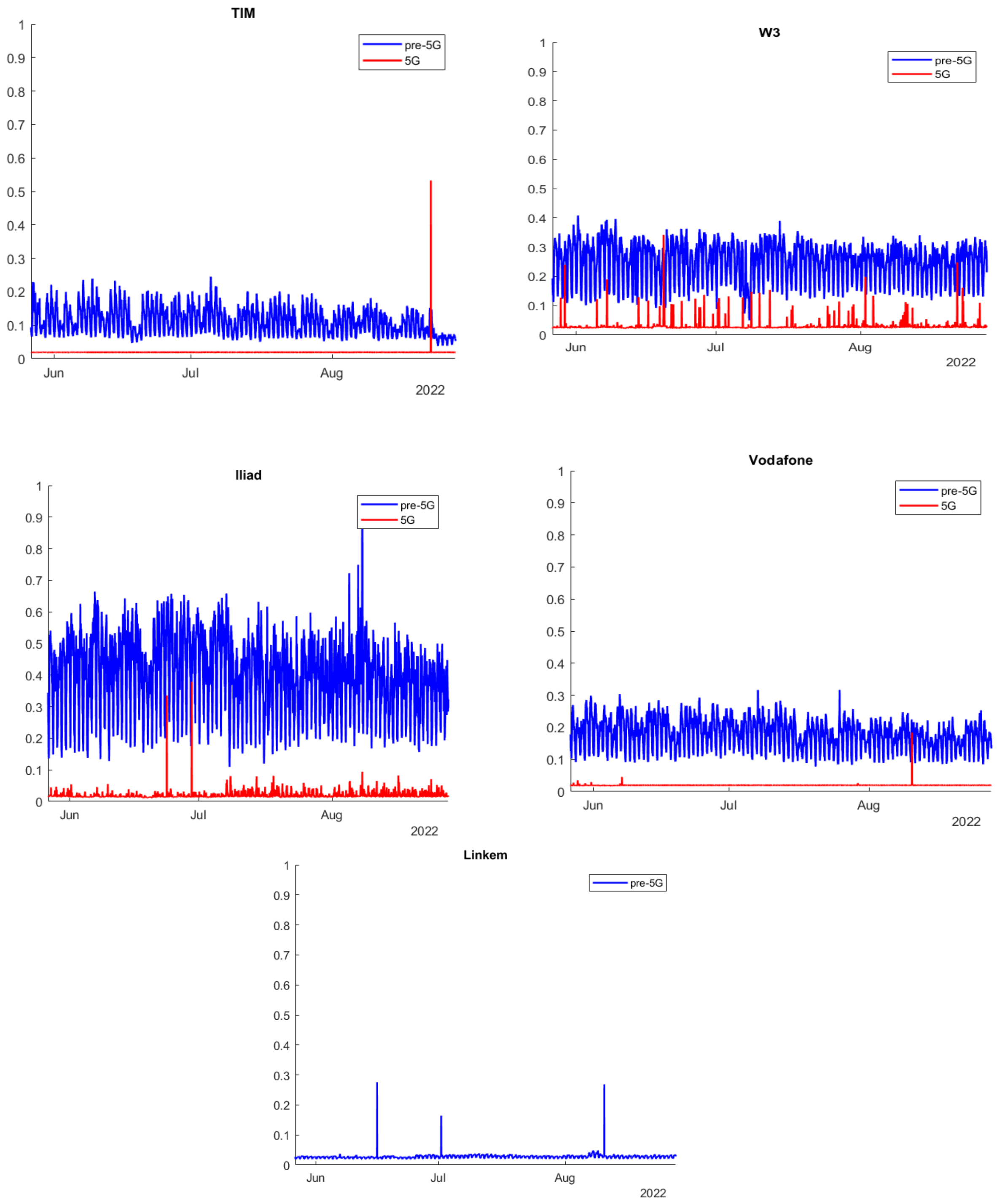

Figure 7: Describes Pre-5G vs 5G exposure for each operator

In the following step, we provide details about the exposure of both pre-5G and 5G over the different frequencies. To this aim, Fig. 8 reports the maximum exposure vs. time for each of the frequencies reported in Tab. 4. Surprisingly, the frequencies experiencing the dramatic increase in exposure versus time are 3547.5 [MHz] operated by the W3 operator, 3630 [MHz] operated by the Iliad network carrier and 3760[MHz] which is operated by TIM ones and we can see that all show a fairly smooth trend while Focusing on pre-5G frequencies (i.e. below 3000 [MHz]) apart from Linkem where it exploits certain frequencies around 3500[MHz] for pre-5G ones.

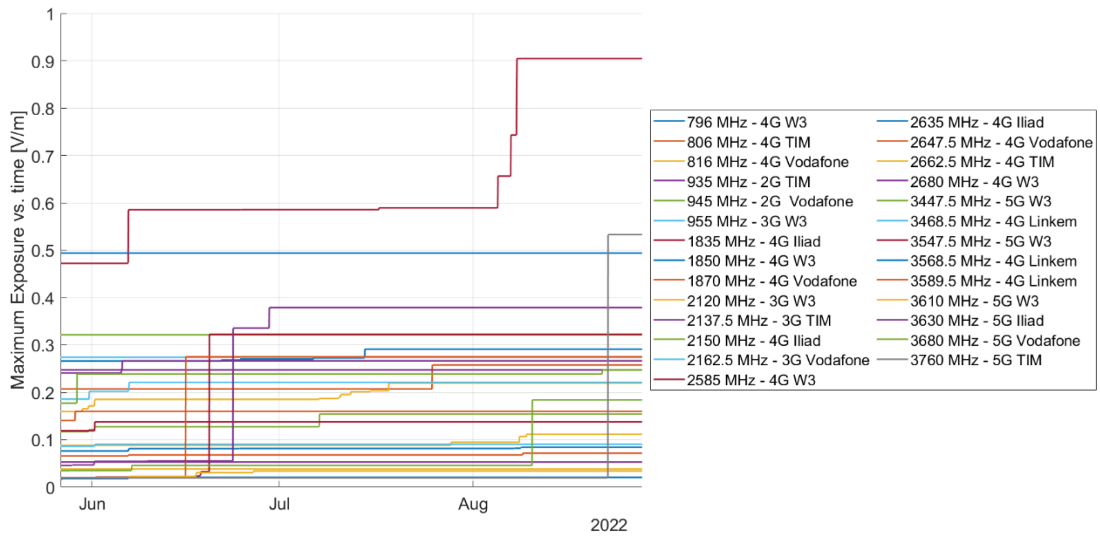

Figure 8: Evolution of maximum exposure vs. time for each frequency band used by multiple operators

Finally, we analyze the occurrence of the 5G peak events. In deep, classifying an hour as a “5G peak” given the exposure observed during the hour is larger than 0.02[V/m] compared to the previous one. As evident from the below mentioned Fig.9, shows the Cumulative number of 5G peak events vs. time, by considering the number of 5G peaks both during working hours/All day which share an equal amount of peak events and the number of 5G peaks during weekends/holidays. Interestingly, it can be summarized that number of 5G peaks overall days is increasing smoothly starting from late May. However, a minute portion of peaks is being experienced during holidays and weekends. Nevertheless, we can conclude that drastic growth in 5G network usage by users is a direct consequence of the increase in the number of 5G peak events.

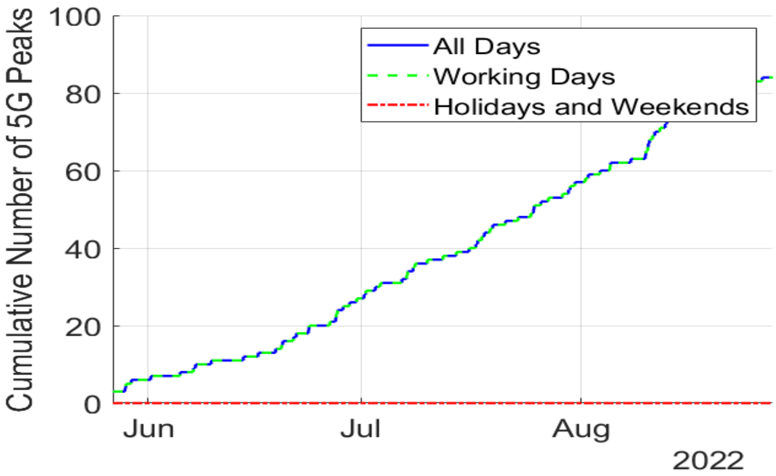

Figure9: Evolution of the cumulative number of 5G peak events

Conclusions

We have initially focused on a three-Month exposure assessment from a location in proximity to Good propagation conditions concerning a base station hosting multiple carriers running both 5G and pre-5G services. Our measurement setup includes a monitoring unit which is connected through a wireless LAN further controlled by software, which is then customized to our requirement at the considered measurement location. From the research and the performance metrics discussed, it is evident that 5G networks are suggesting a growth where our work reveals that, although the share of pre-5G exposure dominates, it can be seen that 5G exposure is not negligible, with 5G peaks that are being noticed both during working days and weekends/holidays. Furthermore, the 5G signals show the largest increase in the maximum exposure vs. time, suggesting that the overall 5G technology growth will be high soon. In future work, we would like to extract suitable models to predict the future trends of the massive exposure.

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