A Methodology to Characterize Power Control Systems for Limiting Exposure to Electromagnetic Fields Generated by Massive MIMO Antennas

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ABSTRACT The fifth-generation (5G) New Radio (NR) cellular network has been launched recently. The assignment of new spectrum bands and the widespread use of Massive MIMO (MaMIMO) and beamforming techniques for better radio coverage are two major features of the new architecture. They imply both opportunities and challenges, one of the most daring one among the latter ones is the research for methods to assess human exposure to electromagnetic fields radiated by the base stations. The long-term time-varying behavior and spatial multiplexing feature of the MaMIMO antennas, along with the radio resource utilization and adoption of Time-Division Duplexing (TDD), requires that the assessment of exposure to electromagnetic fields radiated by 5G systems is based on a statistical approach that relies on the space and time distribution of the radiated power. That, in turn, is determined through simulations based on the actual maximum transmitted power – defined as the 95th percentile of the empirical distribution obtained from historical data of radiated power – rather than on the nominal one. To ensure that exposure limits are never exceeded, a monitoring and control system (usually referred to as Power Lock (PL)) that limits the transmitted power can be used. In this paper we propose a methodology, independent from the specific technical solution implemented by the manufacturer, to characterize such control systems and determine their capability to limit the average power transmitted over a given time interval to a value that keeps the corresponding average exposure to electromagnetic fields below a specified value. Experimental results show the effectiveness of the methodology and that it can also be used to identify when the PL interacts with the higher levels of the MaMIMO system architecture.

INDEX TERMS Radio frequency electromagnetic fields, exposure assessment, massive MIMO, 5G, new radio, measurements, mobile telecommunications, channel power.

I. INTRODUCTION

The fifth-generation (5G) New Radio (NR) system is being rolled out over the world and is expected to provide a solid commercial service within the next few years. Expectations about its performance are high mostly because of the dramatic change in the paradigm of cellular network that it carries along [1]–[5]. Beside signal protocol and network architecture, a major difference with previous-generation mobile systems is the radio interface. Unlike traditional systems that use passive antennas whose radiation pattern is static over time, the NR system uses Massive MIMO (MaMIMO) [6]–[9] technology where active antennas, with different configurations [10], [11], are used to generate multiple radiation lobes with power and shape variable over time, obtained with beamforming techniques [12].

The radiation pattern and gain of an antenna, together with the input power and the characteristics of the propagation channel, determine the distribution of the electromagnetic field (EMF) in the space surrounding the radiant system. For MaMIMO antenna there is no direct proportionality between...
the total transmitted power and the Equivalent Isotropic Radiated Power (EIRP) along the user’s direction. It follows that the evaluation of its total transmitted power does not allow for a deterministic assessment of the actual distribution of the electromagnetic field strength in the space and over time.

Assessment of the exposure to electromagnetic fields, therefore, requires a statistical approach that relies on the space and time distribution of the radiated power [13], [14], as indicated in the standard IEC 62232 [15] and the technical report IEC TR 62669 [16], through numerical methods based on the actual maximum transmitted power (defined as the 95th percentile of the empirical distribution obtained from historical data of radiated power) approach. The operator shall, therefore, ensure that the actual maximum transmitted power threshold is not exceeded during service. This can be done using counters or tools to monitor the transmitted power or EIRP.

When the actual maximum transmitted power approach is implemented through counters, the operator shall collect and monitor data from radio counters to make sure that the transmitted power, averaged over a time interval corresponding to the averaging time of the applicable exposure limits (typically 6 [17] or 30 min [18]), are maintained below the maximum allowed threshold. The International Electrotechnical Commission (IEC) [15], [16] allows that, over a limited time, the cell may exceed the conservative value for at most 5% of the measured values [19], provided that the EMF average exposure keeps below the limit. IEC also describes a control feature based on network counters which can be used to check that the power threshold is never exceeded when averaging over time.

Alternatively, the operators can activate automatic tools to monitor and control the transmitted power (or EIRP) of a MaMIMO antenna to ensure that the threshold values configured for each MaMIMO antenna are not exceeded, as described in [20]. Such tools are usually referred to as Power Lock (PL) features, and their main operational characteristics will be described in Sect. II.

This paper presents a methodology to test the functionalities of a power control and limitation system. The main purpose of the methodology is to verify that such power lock feature meets the requirement of limiting the transmitted power of the traffic channel only, without acting on the control channel. It is organized as follows: after detailing the main functional characteristics of the PL in Sect. II, an overview of the 5G NR grid structure is provided in Sect. III, the proposed methodology and the measurement setup for its validation are presented in Sect. IV and V, respectively. Experimental results are reported and commented in Sect. VI, while conclusions are drawn in Sect. VII.

II. POWER LOCK FUNCTIONAL DESCRIPTION

Documents [15], [16] by IEC and [20] by the Next Generation Mobile Networks (NGMN) Alliance do not provide any details about the implementation of the PL feature for controlling and limiting the radio frequency (RF) transmitted power, because it is considered a specific task to be performed by the radio equipment manufacturer. Given that the latter is unlikely to provide detailed information about how such feature works in its own implementation, this section presents a description of the principles of the main PL functionalities, enriched by the information acquired during the test session.

The PL has to monitor the power transmitted by the MaMIMO system at a very high rate (possibly once in each transmission time interval (TTI) or every few milliseconds at most) and automatically limit the maximum value so that the average transmitted power over a reference time interval does not exceed the allowed threshold. Practically, for, say, every TTI the feature has to monitor the RF output power of every transceiver module (TRx), which then feeds the MaMIMO antenna, typically made of an array of dipoles so that every TRx might be connected to one or more of them. Moreover, the RF power is in a direct relationship with the transmitted EIRP through the antenna gain. Therefore, knowing the maximum antenna array gain, the radiated power can be monitored in each TTI and, in turn, the average power transmitted in a given interval (e.g., 6 min) can be obtained.

The purpose of the PL is not simply to calculate the average transmitted power, which task is performed by specific counters for measuring the key performance indicators (KPIs) of the network. Instead, its goal is to ensure that the average transmitted power over the assigned time interval does not exceed the allowed threshold, so the PL has to establish when and how to limit the maximum power that can be transmitted by the MaMIMO antenna in the remaining portion of the reference time interval based on the average power transmitted in the initial portion of the interval.

For example, assuming that the instantaneous maximum power $P_{\text{max}}$ is initially set at 100 W and the threshold for the average power over 6 min at 25 W (25% of $P_{\text{max}}$), if for the first minute the average transmitted power is equal to $P_{\text{max}}$ (i.e., the antenna constantly transmits at $P_{\text{max}}$), then for the remaining 5 min $P_{\text{max}}$ will be reduced to 10 W, so that the average power over the whole 6 min will be $P_{\text{avg}} = (1 \cdot 100 + 5 \cdot 10)/6 = 25$ W. As a consolidated practice adopted by all manufacturers to all technologies, the maximum instantaneous power $P_{\text{max}}$ that can be transmitted is tuned through the Operational Service System (OSS) in the baseband unit (BBU) of the MaMIMO antenna, the maximum power amplifier output being its upper bound.

In the tested system the amount of power reduction is fixed, that is the PL does not calculate it and sets it to the average threshold. In other words, when the feature is activated the maximum instantaneous power that the MaMIMO antenna can transmit is either equal to the maximum power or to the power threshold. Referring to the previous example, the maximum power that can be transmitted is, therefore, either equal to 100 W when the PL is inactive or 25 W when the PL is operating. As a result, in the case that the MaMIMO antenna starts transmitting at 100 W, in order to ensure that the average power is equal to 25 W, the feature should reduce immediately the maximum transmitted power down to 25 W.
As said before, the implementation of the feature is completely up to the manufacturer (and, as such, patented), especially with reference to when the PL activates and how it reduces the RF power. The only piece of information that was disclosed to the Authors is that the PL interacts with the downlink scheduler to dynamically reduce the momentary output power by decreasing the power of the Physical Downlink Shared Channel (PDSCH) and/or reducing the assigned Resource Blocks (RBs). Moreover, the feature ensures that no change in the NR coverage is experienced by users by operating only on traffic channels, not on control channels.

It must be said, however, that decreasing the power of the traffic channels or reducing the number of RBs assigned to a user could lead to a degradation of the quality and performance experienced by the users when the system is operated in high traffic conditions.

III. 5G NEW RADIO (NR) GRID STRUCTURE

In this section, we present the key principles of the physical layer of 5G NR that are important for RF exposure assessment [21].

The 5G NR frame structure is shown in Fig. 1. It relies on Orthogonal Frequency-Division Multiplexing (OFDM) and supports operation in the spectrum ranging from sub-1 GHz to millimeter-wave bands. Two frequency ranges (FRs) are defined in the 3rd Generation Partnership Project (3GPP) technical specifications [22]–[24]:

- FR1: 450 MHz to 7,125 × 10^3 MHz, commonly referred to as sub-6 GHz;
- RF2: 24.25 GHz to 52.6 GHz, commonly referred to as millimeter waves.

With the purpose of ensuring the 5G NR and LTE coexistence on the same frequency band, the time length of the 5G NR frame is 10 ms and consists of 10 subframes, each having a time length of 1 ms, as in the LTE system. Unlike the LTE, 5G NR uses a flexible numerology characterized by the parameter \( \mu \) [23]. The flexible numerology allows 5G NR to provide a wide range of services requiring different latency and capacity, offering the possibility to manage low latency services instead of only high data transmission applications [25]. Moreover, as an additional difference with the LTE, 5G NR allows simultaneous multi-numerology utilization. The 5G NR multi-numerology structures was also studied in [26]–[31], whereas one of the first studies on a framework that provides several different services simultaneously in a unified framework applying the multi-numerology paradigm was [25].

In the 5G NR frame structure, each subframe consists of \( 2^\mu \) time slots, in order to cope with the wide range of applications for which it was designed and the large spectrum availability. Each slot of \( 1/2^\mu \) ms contains 14 OFDM symbols (12 OFDM symbols in case of extended cyclic prefix). Accordingly, each symbol duration is equal to \( (14 \cdot 2^\mu) \) ms for extended prefix). Therefore, the number of symbols contained in each subframe depends on the value of \( \mu \): larger values of \( \mu \) allow for more symbols in the same subframe.

Different numerologies are associated to different OFDM subcarrier distances. In particular, the subcarrier spacing is \( 2^\mu \cdot 15 \) kHz, with \( \mu = \{0, 1, 2, 3, 4\} \). Subcarrier spacing of 15 kHz, 30 kHz and 60 kHz are used in sub-6 GHz band (FR1), while 60 kHz and 120 kHz are used for millimeter-wave band (FR2). Instead, the 240 kHz spacing is reserved...
for non-data (signaling) channels. Note that for $\mu = 0$
NR uses the same spacing of the LTE subcarrier (15 kHz),
thus ensuring full compatibility between the two systems on
the same frequency band. An NR carrier is made of up to
3276 subcarriers. The maximum bandwidth of each NR car-
rier is 100 MHz for sub-6 GHz band (FR1) and 400 MHz for
millimeter-wave band (FR2). Both values are much greater
than the LTE bandwidth, which is limited to 20 MHz. In order
to manage different numerologies simultaneously, in 5G NR
the Bandwidth Part (BWP) has been introduced, which con-
sists of a group of contiguous Physical Resource Blocks
(PRBs) defining a fixed portion of the frequency band over
which the communication takes place with a given numerol-
ogy [24]. Each BWP has its own numerology that fixes the
cyclic prefix length and the subcarrier spacing. Furthermore,
unlike the LTE, since 5G User Equipments (UEs) need to
monitor only the assigned BWPs, they don’t need to scan the
whole bandwidth, thus reducing the UE’s power consump-
tion. The Resource Grid (RG) [23] is a time-frequency rep-
resentation of the radio resources available for transmission.
RG is characterized by one subframe in the time domain and
full carrier bandwidth in the frequency domain (see Fig. 1).
Since 5G NR supports different numerologies, there is a
different RG extension for each of them. The smallest unit
of the RG is represented by one subcarrier in the frequency
domain observed for the time duration of one OFDM symbol,
named Resource Element (RE). REs are grouped into PRBs
consisting of 12 consecutive subcarriers in the frequency
domain.

Analyzing the RG is extremely complex, and the reader is
referred to [23] for a thorough discussion about it. Nonethe-
less, since detection and decoding of the Control and Syn-
chronization signals is particularly useful and interesting for
the assessment of exposure, in the following we describe
those signals briefly. In 5G, Synchronization Signal and
Physical Broadcast Channel (PBCH) are packed as a sin-
gle block (Fig. 2). More specifically, the Synchronization
Signal/Physical Broadcast Channel (SS/PBCH), also named
Synchronization Signal Block (SSB), occupies 240 contigu-
os subcarriers and four contiguous OFDM symbols. It con-
tains four different types of signals: the Primary Synchron-
ization Signal (PSS), the Secondary Synchronization Signal
(SSS), the PBCH and the PBCH Demodulation Reference
Signal (PBCH-DMRS). SSBs are grouped in blocks named
SSB bursts (see Fig. 2), transmitted in the first 5 ms of the
frame, with a configurable periodicity of 5 ms, 10 ms, 20 ms,
40 ms, 80 ms or 160 ms. Block patterns are a function of the
FR and subcarriers spacing, and the 3GPP technical specifi-
cation (see [24, §4 Synchronization Procedures]) defines five
different cases (i.e., A, B, C, D, E) for a total of eight possible
configurations.

The maximum number of SSBs in a single burst is indi-
cated with $L_{\text{max}}$ and ranges from 4 or 8 for cases A, B and
C (FR1) to 64 in cases D and E (FR2). SSBs grouped in
an SSB burst are used to implement initial UE radio access and are involved in the beam sweeping procedure. Each SSB is associated to a different beam which points to a different direction in the space. The UE, during the initial radio access setup, locks to the beam that provides the strongest received signal (see Fig. 3).

**IV. PROPOSED METHODOLOGY**

Since it is unlikely that a radio equipment manufacturer provides detailed information about how the power monitoring and controlling feature – hereafter named Power Lock (PL) – is implemented, and how it interacts with the downlink scheduler in order to dynamically reduce the instantaneous transmitted power, the proposed methodology is focused on the assessment of the PL’s capability to ensure that the EMF exposure complies with limits, usually set as the average over a given time interval. Moreover, the methodology is independent of the specific technical solution and implementation of the PL and can, therefore, be applied to any commercial and experimental solution without loss of generality. As a matter of fact, it is based on a black-box approach consisting of a simple measurements procedure that, furthermore, can be easily replicated during the whole MaMIMO antenna’s life cycle to check that the PL maintains its designed operational features over time.

To better understand the methodology, it is useful to introduce the main quantities that we will refer to:

- \( P_t \) is the instantaneous power transmitted by the MaMIMO system;
- \( P_{\text{max}} \) is the maximum instantaneous power that can be transmitted by the MaMIMO system at any time (i.e., the upper bound of \( P_t \), so that \( P_{\text{max}} \geq P_t \));
- \( F_{\text{TDC}} \) is the Technology Duty Cycle Factor, a deterministic scaling factor representing the fraction of the signal frame reserved to the downlink transmission [16];
- \( P_{\text{avg, max}} \) is the maximum average power that can be transmitted by the MaMIMO system over a time interval \( \tau \) of duration 6 min [17] or 30 min [18]. If PL is inactive and \( P_t \) is constant and equal to \( P_{\text{max}} \), then \( P_{\text{avg, max}} = P_{\text{max}} - |F_{\text{TDC}}| \), whereas if PL is active, there is no such relation because its value is imposed by PL;
- \( E_0 \) is the maximum average EMF exposure over \( \tau \) allowed for the specific MaMIMO system on which the PL is tested. \( E_0 \) is set according to the radiation-protection legislation under the condition of simultaneous exposure to high-frequency EMF fields generated by all the systems installed at the same site or at nearby sites and supposing that the effects of exposures are additive;
- \( P_0 \) is the maximum average power that results in an exposure equal to \( E_0 \) over \( \tau \).

For a proper assessment of the PL operating characteristics, the methodology requires that \( P_t \) is equal to the maximum allowed power at all times during the validation procedure, which in turn implies that the full downlink capacity of the MaMIMO antenna under test is deployed. To operate under such conditions, one or more UEs capable of forcing high data-rate download transmission are required. Indeed, if such condition is not met the PL may possibly never activate because the average power may never reach the maximum allowed average value \( P_0 \).

The performance assessment of the PL can be run through the methodology described in the following:

1) **Fixing of \( P_0 \).** It is first required that \( P_0 \) is fixed through a numerical or experimental approach that leads to determining the constant power \( P_t \) that results in an average EMF exposure over \( \tau \) equal to \( E_0 \). During this operation, the PL is off, which condition will be labeled as \( \text{PL}_{\text{off}} \), and it is imposed that \( P_{\text{avg, max}} = P_0 \). In fact, to make sure that EMF exposure during normal operation of a MaMIMO system without PL is compliant with the limits, \( P_{\text{avg, max}} \) can be at most equal to the power \( P_0 \) that results in an exposure equal to \( E_0 \). We observe that at the end of this step also the value of \( P_{\text{max}} \) is determined: \( P_{\text{max}} = P_0 + |F_{\text{TDC}}| \).

As introduced in Sect. II, the (maximum) instantaneous power \( P_t (P_{\text{max}}) \) that can be transmitted is set through the OSS in the BBU of the MaMIMO antenna.

2) **Increase of \( P_{\text{max}} \).** \( P_{\text{max}} \) is increased by an amount \( \Delta P \) and, since \( P_{\text{avg, max}} \) is a known and fixed portion of \( P_{\text{max}} \) when PL is off, \( P_{\text{avg, max}} \) is also increased by the same amount: \( P_{\text{avg, max}} = P_0 + \Delta P \). Similarly to step 1, \( P_{\text{max}} \) has been increased by operating on the OSS in the BBU of the MaMIMO antenna.

To confirm that the MaMIMO system has been correctly configured with the new \( P_{\text{max}} \), the average EMF exposure over \( \tau \) is measured: the resulting EMF strength should increase by the same amount \( \Delta P \). Furthermore, since PL is off, both traffic and control channels strength should increase.

3) **Activation and validation of PL.** With the increased value of \( P_{\text{max}} \), PL is activated (i.e., \( \text{PL}_{\text{on}} \)) and configured to limit the average power transmitted over \( \tau \) to \( P_0 \). This means that \( P_t \) will gradually decrease from the initial value \( P_{\text{max}} \) so that its average value over \( \tau \) is equal to \( P_0 \).

Measurements of the EMF exposure will give evidence that its average value is compliant with \( E_0 \) and that PL only affects traffic channels while having control channel transmitted at the maximum power \( P_{\text{max}} \).

The experimental activity to validate the proposed methodology requires a different test for each step described above. To change the system configuration, tests must be interleaved with idle time intervals during which only control channels are active to keep the system alive and reachable by the UEs.

Before proceeding with the presentation of the measurement setup and discussion of the experimental results, we wish to stress, once again, that our proposal refers to a methodology to assess the performance of a PL feature,
i.e., its capability to reduce the radiated power to maintain exposure to EMF below the applicable limits. As such, the measurement of EMF exposure itself is not the focus of this paper, neither are we proposing a method for a better assessment of exposure levels. As a matter of fact, as explained above, EMF strength measurements only come into play to verify the effectiveness of the PL’s action. For that specific task, we used the procedure detailed in [32], although we are aware that the issues and challenges related to EMF measurements in 5G technology are wide and still open, as testified by the increasing number of papers focusing on them (see [21], [32]–[36] as an example).

V. MEASUREMENT SETUP

The proposed exposure assessment methodology was validated in a Line-of-Sight (LOS) environment in the city of Rome, Italy (see. Fig. 4) using a commercial Time-Division Duplexing (TDD) 3.5 GHz MaMIMO antenna system manufactured by Huawei. The main characteristics of the transmitted 5G signal are reported in Tab. 1 and Fig. 5, while a summary of the tests used in the experimental campaign reported in Sect. VI to validate the methodology is listed in Tab. 2.

Table 1. 5G signal configuration.

| Parameter            | Value            |
|----------------------|------------------|
| Center frequency     | 3680.01 MHz      |
| Bandwidth            | 80 MHz           |
| Duplexing            | TDD              |
| Frame configuration  | 8 : 2            |
| Subcarrier spacing   | 30 kHz           |
| \( P_{\text{TDC}} \) | -1.3 dB          |
| \( \mu \)            | 1                |
| Symbol duration      | 33.3 \( \mu \) s |
| Cyclic Prefix (CP)   | 4.7 \( \mu \) s  |
| slots/frame          | 20               |
| slots/subframe       | 2                |
| symbols/slot         | 14               |
| SSB center frequency | 3649.44 MHz      |
| SSB configuration    | Case C           |
| SSBs per burst       | 6                |

Table 2. Test configuration.

| Test no. | Power Lock | \( P_{\text{max}} \) | \( P_{\text{avg,max}} \) | \( P_{\text{TDC}} \) |
|----------|------------|----------------------|--------------------------|---------------------|
| 1        | OFF        | 46 dBm               | 44.7 dBm                 | -1.3 dB             |
| 2        | OFF        | 51 dBm               | 49.7 dBm                 | -1.3 dB             |
| 3        | ON         | 51 dBm               | 44.7 dBm                 | -1.3 dB             |

Table 3. Channel Power measurement configuration.

| Parameter                  | Value            |
|----------------------------|------------------|
| Center frequency           | 3680.01 MHz      |
| Integration Bandwidth (IB) | 80 MHz           |
| Resolution Bandwidth (RBW) | 100 kHz          |
| Video Bandwidth (VBW)      | 300 kHz          |
| Sweep Time (SWT)           | 100 ms           |
| Trace                      | Average (\( n = 200 \)) |
| Detector                   | RMS              |
| Trigger                    | continuous       |
the operational principles and technical details of the PL.

In this section we present the results of the experimental measurements. To comply with the requirement that the full download traffic (i.e., the RBs) and the instantaneous transmitted power \( P_t \) were sampled at the MaMIMO antenna input every 1 s and 2 s, respectively, through a software provided by Huawei. It should be noted that, in standard measurement procedures, RB and \( P_t \) data are not extracted with the same time resolution. CP measurements, due to the SWT and Trace procedures, RB and \( \tau \) respect to the signal center frequency, pattern, periodicity) transmitted by the MaMIMO. Details about the measurement procedure can be found in [32].

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To comply with the requirement that the full download capacity of the MaMIMO system is deployed, as explained in Sect. IV, two 5G phones have been placed in the proximity of the measurement point and configured with a continuous UDP data transmission. Preliminary tests have shown that using only one UE would not allow for a complete saturation of the RBs transmission capacity. The distance between the UEs and the receiving antenna was optimized to minimize the effect of the uplink transmission on channel power measurements.

### VI. EXPERIMENTAL RESULTS

In this section we present the results of the experimental validation of the methodology, described in Sect. IV, to characterize the performance of a Power Lock (PL) feature fixing the averaging interval \( \tau \) according to [17], i.e., \( \tau = 6 \) min. We recall that the methodology relies on a black-box approach that does not require a preliminary knowledge of the operational principles and technical details of the PL.

The procedure implied by the characterization principles on which the methodology is based requires that we execute three tests, one for each operational condition (see Tab. 2). Measurements of \( P_t \), CP and Resource Blocks (RBs) are shown in Fig. 6. As already explained in the description of the methodology, some idle time is required between tests to change the equipment settings, yet keeping the system alive. Measurements have been run continuously during tests and idle times, and also for some time before test 1 and after test 3.

#### A. FIXING OF \( P_0 \)

\( P_0 \) is fixed with test no. 1 (label “\( P_0; \text{PL}_{\text{off}} \)” in Fig. 6) by forcing the MaMIMO system to transmit the maximum number of available RBs constantly thus keeping \( P_t \) as constant as possible. Such condition is not always met and RBs decrease randomly falling from the 217 to about 180 (see the bottom facet of the plot). If we focus on times before 10:34:17 (red dashed vertical line), we see that \( P_t \) doesn’t seem to be very sensitive to such decrease, mostly because of the large dynamic of the logarithmic scale that doesn’t allow to appreciate variations in the order of a few Watt at most. To better investigate this behavior, we compared \( P_t \), CP and RB before and after 10:34:17 (see the white inset in Fig. 6) on a linear scale. Fig. 7 clearly shows that \( P_t \) follows RBs almost perfectly and that whenever a reduction in RB occurs it implies a reduction in \( P_t \).

The same figure is also helpful to explain the behavior of CP measurements over time shown in Fig. 6: as expected, the radiated power that reaches measurement chain 2) described in Sect. V decreases with \( P_t \). We wish to underline that CP is the average of 200 traces of 100 ms each and therefore its curve is smoothed and delayed with respect to \( P_t \). At the end of the procedure, \( P_0 \) has been determined to be \( P_0 = 44.7 \) dBm, so that \( P_{\text{max}} = 46 \) dBm (see Tab. 2).

The top trace of Fig. 8a shows the EMF strength \( E \) over time once the value of \( P_0 \) has been assessed. The observation interval is 20 ms, i.e., the length of two frames. The first 5 ms are reserved to the transmission of the SSB burst. The trace shows that the maximum amplitude for both traffic and control channels is \( E = 0.26 \) V/m. This is only a fraction of \( E_0 \) that has been determined according to the restriction on human exposure explained in Sect. IV: namely, given that the RBW of the measurement chain 2) presented in Sect. V
is only one fortieth of the 5G bandwidth, we have \( \hat{E} = E_0/\sqrt{80/2} \approx E_0/6.32 \text{ V/m} \).

During this specific acquisition the UE the RBs fluctuated around the full downlink capacity: this is the reason why the traffic channels are not constant at \( \hat{E} \).

Since this is the exposure condition that will be used as a reference for the validation of steps 2) and 3) of the methodology, in Fig. 8b we have reported the same quantities of Fig. 8a in logarithmic units, normalized to \( \hat{E} \) obtained in step 1).

**B. INCREASE OF \( P_{\text{max}} \)**

Test no. 2 (label “\( P_0 + \Delta P; \text{PLoff} \)” in Fig. 6) shows what happens when \( P_{\text{max}} \) is increased by \( \Delta P = 5 \text{ dB} \) and PL is inactive (see Tab. 2). Exploiting the full download capacity by forcing the transmission of the maximum number of RBs, as shown in the bottom trace of Fig. 6, we see that the instantaneous power \( P_t \) increases by \( \Delta P \) (see top trace) and the CP also increases, although the measured increment is slightly less than 5 dB that, however, is a plausible value given the 1.5 dB uncertainty (\( k = 2 \)) for that measurement chain.

Because of the inactivity of PL, the \( E \) field increases to 0.46 V/m for both the traffic and control channels, as shown in the middle trace of Fig. 8a. Furthermore, the corresponding middle trace of Fig. 8b confirms that the increase has been of the same amount as \( P_{\text{max}} \), i.e., \( \Delta E = 5 \text{ dB} \). It is apparent that because of the increase of \( P_t \) and inactivity of PL, \( E > \hat{E} \).

By looking at the idle time between test no. 1 and 2 (see hours 10:42:10, blue dashed vertical line) we see an increase in \( P_t \) by \( \Delta P \) even if there is no data transmission. This is because during that interval traffic channels are off, while control channels are active (i.e., SSBs are still transmitted) to keep the system alive and reachable by the UE. This will be discussed in details in Sect. VI-D, which discusses the behavior of the demodulated power of the PBCH-DMRS during both idle intervals and active transmission.

**C. VALIDATION OF PL**

The action of PL on \( P_t \) is tested with test no. 3 (label “\( P_0 + \Delta P; \text{PLon} \)” in Fig. 6). We see that at the very beginning of the test, when data transmission occurs with the maximum RBs, \( P_t \) is transmitted at the same level as test no. 2, i.e., under condition PLoff. This is because PL limits \( P_t \) so that the average value does not exceed \( P_0 \). Indeed, after a few seconds where \( P_t = P_0 + \Delta P \), PL senses that \( P_0 \) is being approached and it limits \( P_t \) to \( P_t = P_0 \) without limiting the number
of RBs. The PL adjusts the power of the PDSCH without reducing the assigned RBs.

Because of the 20 s averaging time, CP measurements do not follow the instantaneous variations of $P_t$ and its level during the test goes to the same level of test no. 1.

The same figure shows that during the test there is a strong reduction in the number of RBs transmitted without a reduction of $P_t$. According to the manufacturer, this happens because the PL is interacting with the downlink scheduler in such a way that the result is a reduction of the assigned RBs yet transmitting each RB at a higher power. Moreover, we can observe that the CP fluctuates in this period following the RBs. The explanation for this behavior has been provided by the system manufacturer that claimed that during that interval the MaMIMO antenna is performing a beam optimization, both in terms of power and RBs, and that the beam swings so that it is not always pointed toward the UEs.

The $E$ field strength for this test is shown in the bottom trace of Fig. 8a, where we see that, thanks to the action of PL, traffic channels are clearly pushed down to the reference level $E$ of test no. 1 while, as expected, the SSBs are affected by the $\Delta P$ increase and are therefore at $E = 0.46$ V/m. The 5 dB ratio between the traffic and control channel is apparent in the bottom row of Fig. 8b.

Note that PL is activated during the idle time between test no. 2 and 3, around hours 11:07:00 (brown dashed vertical line). We can see from Fig. 6 that $P_t$ during that interval is the same as the one transmitted during idle time immediately before data transmission of test no. 2 and the one transmitted during a temporary data transmission switch off occurred during test no. 2. Again, this happens because during that time SSBs are active and transmitted at the maximum allowed power $P_{\text{max}}$, which is now $P_{\text{max}} = 51$ dBm.

**FIGURE 8.** Zero Span $E$ field strength.

**FIGURE 9.** Demodulated power of the PBCH-DMRS.

### VII. CONCLUSION

In this paper we have proposed and validated a methodology to characterize a tool (named Power Lock (PL)) designed for monitoring and controlling the average power transmitted by an MaMIMO antenna so that the exposure to electromagnetic fields generated by 5G systems, averaged over a reference interval, complies with exposure limits.

The methodology requires that the transmitted power and resulting EMF strength are monitored under three different conditions, thus the validation procedure requires three different steps to: 1) determine the average power $P_0$ that
guarantees that the EMF exposure complies with the applicable limits; 2) increase the maximum power transmitted by the MaMIMO antenna and check that both control and traffic channels amplitude increases; 3) turn the PL feature on and verify that it limits the traffic channels power without affecting the control channels.

Experimental results proved that the proposed methodology matches the purposes and also allowed to gain insight into some other specific operational features of the PL. More specifically, results confirm the effectiveness of the methodology in demonstrating that the PL feature limits the average transmitted power of the traffic channels, regardless of the configured maximum power, without affecting the control channels, and that the EMF average exposure limit is not exceeded as well.

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