FINAL PUBLISHABLE REPORT

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1 Overview

Current radiofrequency electromagnetic field (RF-EMF) exposure limits have become a critical concern for fifth generation (5G) mobile network deployment across Europe. Regulation is not harmonised and in certain countries and regions goes beyond the guidelines set out by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). This project produced specific RF-EMF exposure measurement guidance for 5G massive multiple-input-multiple-output (mMIMO) base stations which were disseminated to technical, business and regulatory communities to support the development of effective regulation and enable 5G implementation that balances performance with public safety.

2 Need

Currently, associated wireless industries employ 1.3 million people in the EU, representing a contribution of €160bn to the economy. 5G is set to become a basic requirement in the fields of eHealth, smart grids, smart cars, connected homes, entertainment, and smart asset tracking systems. Reliable mobile and fixed connectivity will make new digital applications a reality, e.g. virtual and augmented reality, autonomous driving, artificial intelligence, smart manufacturing, and precision farming. The European telecommunications industry plays a crucial role in the development of emerging wireless technologies for 5G mobile networks. The move to wider bandwidths at different RF bands and the industrial adoption of complex new radio signals in 5G mMIMO base station systems, places greater demands on the measurement equipment used in production and testing, and in research and development. While the 5G standardisation processes are ongoing, the key challenges are a lack of practical metrology to support new radio RF exposure assessment. This project directly addressed these challenges faced by the 5G technical, business and regulatory communities as well as supported the development of the relevant 5G infrastructure and standards.

The rollout of 5G networks is leading to fundamental changes to our society, impacting not only consumer service but also industries embarking on digital transformations. In Europe, exposure to RF-EMF is regulated based on the 1998 or 2020 guidelines of the ICNIRP. Within the European Union (EU) legal framework these guidelines are enshrined in Council Recommendation 1999/519/EC for general public. However, certain EU member states have imposed stricter EMF exposure limits which are significantly lower than the ICNIRP guidelines. For example, in Switzerland and Italy, a different regulation has been put in place where the current RF-EMF exposure limits are 4 V/m and 6 V/m, respectively, which is much stricter than the ICNIRP guidelines at 61 V/m. This more stringent exposure limit has had an impact on 5G network rollout and deployment.

Proximus Belgium (Belgium's leading mobile network operator and primary supporter of this SIP) has identified the need for robust methods to measure the realistic RF-EMF exposure from 5G base stations. Current measurements of RF-EMF exposure from third generation (3G) and fourth generation (4G) base stations include an exclusion zone (a compliance boundary around the BS with no access to general public), based on the assumption that the theoretical maximum power is transmitted in every possible direction for a defined time-period. However, the beamforming mMIMO base stations employed in 5G new radio allow energy to be focussed in sharp high-gain beams in the direction of a specific mobile user. This means that it is difficult for operators to deploy 5G mMIMO on sites with pre-existing 3G and 4G base stations. Regulators, operators and 5G equipment suppliers therefore require up-to-date, reliable and agreed assessments of RF-EMF exposure levels to support consistent and effective 5G regulation and network design.

Previously, EMPIR project 14IND10 MET5G developed 5G testbed capability that sought to establish metrological traceability for mMIMO base stations and measurement capability in generating traceable known EMF measurements. This project developed and validated these measurement techniques for RF-EMF exposure, made recommendations on how to properly measure RF-EMF exposure from 5G mMIMO base stations to the relevant technical, business and regulatory communities (e.g., CENELEC, IEC, IEEE, ITU, Proximus, Ofcom, ANFR, Swiss OFCOM, Swiss Federal Office of Environment).

3 Objectives

The overall objective is to create impact from the use of the hardware and metrological capabilities of JRP-14IND10 MET5G by establishing real-world 5G scenarios in a laboratory environment, developing metrology for RF exposure from 5G Massive MIMO base stations, and validating the methods with real-world measurements. The specific objectives of the project are:

1. To establish a realistic, rigorous measurement capability for traceable RF-EMF measurement of 5G new radio new radio mMIMO base stations. This will include RF-EMF assessment of real-world 5G new radio mMIMO base stations based on RF-EMF measurement and data processing methods/protocols of 5G mMIMO base stations.
2. To make recommendations to the technical, business and regulatory communities (e.g. EU regulatory bodies and ICNIRP, ITU, 3GPP, CTIA, IEEE, ETSI, GSMA) on how to robustly measure RF-EMF from 5G new radio mMIMO base stations in order to establish appropriate base stations exclusion zones for 5G.

4 Results

The relevant key achievements of the project with respect to the aforementioned technical objectives are:

1. **To establish a realistic, rigorous measurement capability for traceable RF-EMF measurement of 5G NR mMIMO BSs**

   Top-level achievement summary:

   In the context of 5G exposure measurements, there are concerns about the use of the maximum worst-case exposure to quantify the exposure of 5G Base Stations (BS). Different contributions tend to demonstrate that this would not be optimum due to the use of complex adaptive beamforming technologies for 5G BSs for which current metrological methods are not well established. This technical objective focused on traceability establishment and development of suitable RF-EMF measurement methods in the context of 5G mMIMO base stations serving different number of mobile users within realistic real-world environments and scenarios.

   This technical objective starts with NPL, Keysight and SURREY jointly establish a new traceable RF-EMF measurement capability for 5G NR mMIMO transmitter, which consists of a fully user-controllable mMIMO beamforming testbed system and two different types of RF-EMF measurement systems – one established based on antenna array and software defined radio (SDR) system, and another one established based on triaxial isotropic field probe and spectrum analyser. To achieve traceability, all these measurement systems have been calibrated traceable to the UK national standard. In preparation for the measurement campaigns, modifications to the established fully user-controllable mMIMO beamforming testbed system were made so it could be used with static zero-forcing precoding and beamforming operations; for single- to multiple-user MIMO fixed static beamforming scenarios; with different combinations of data traffic flow patterns. Consequently, several indoor and outdoor RF-EMF measurement campaigns have been successfully completed (3 indoor and 2 outdoor) including the assessment of a commercial 5G beamforming mMIMO BS in an outdoor environment.

   During the measurement campaigns various varying factors such as number of users, position of users and data duty cycles have been considered. Also, where possible, several other varying factors that influence the RF-EMF of mMIMO system have also been investigated: 1) spatial RF-EMF variation at different locations; 2) temporal RF-EMF variation at a fixed location; 3) mMIMO operating with different number of active transmitting antennas; 4) different line-of-sight and non-line-of-sight scenarios. By considering these varying factors, one would enable the insight understanding into the statistical nature of mMIMO RF-EMF exposure distribution, if feasible, over the whole area or some selected locations, and to assess into how their relevant changing exposure over time are affected by the fluctuation of the environment, number and position of the different users, changes of data usage activities (i.e. data traffic pattern) of the active users. Note that the user-controllable mMIMO beamforming testbed is envisaged to produce static beam(s) for different aforementioned factors whereas the live commercial 5G BS system is envisaged to produce adaptive beam(s) without any specific knowledge on the beam patterns and its relationship with the aforementioned factors.

   Given the nature of the mMIMO adaptive beamforming transmission, where the spatial pattern of transmission (i.e., number of beams used, direction of the beams) can change every few milliseconds, it makes sense that the new metrology for 5G BS is based on statistical RF-exposure models, either based on system level simulations or real-world measurement data acquired from deployed 5G BS. Some evidence already points out that such model provides realistic and implementable exclusion zones for 5G BSs. Therefore, based on the obtained experimental-based evidence on the stochastic nature of mMIMO operation, the measurement data have been evaluated for identification of the suitable measurement methodologies/protocols and approaches on how to apply statistics over data processing for rigorous RF-EMF assessments of 5G NR mMIMO base station systems. The results have been presented to the Primary Supporter. Overall, the work undertaken to achieve this objective, the project has produced one key output: a validation report describing rigorous measurement capability for traceable RF-EMF measurement of 5G NR mMIMO BSs / systems based on RF-EMF measurement and data processing methods/protocols. This report (entitled 'D1') and the relevant measurement data can be accessed and downloaded via the following open access link – http://empir.npl.co.uk/5grfex/publications/. This objective was successfully completed.

Strategy and approaches:

This technical objective has been divided into two parts.

1. *Traceable 5G NR mMIMO RF-EMF measurement testbed development:*
   1.1. Testbed and traceability establishment
   1.2. Testbed modification enabling consideration of various varying factors.
2. *5G NR mMIMO RF-EMF measurement campaigns and measurement protocol evaluations:*
   2.1. SURREY mMIMO system in indoor environment
   2.2. SURREY mMIMO system in outdoor environment
   2.3. Commercial 5G BS system in outdoor environment
   2.4. Measurement protocol evaluation of experimental-based evidence.

The adopted strategy enabled confidence over the identification of suitable measurement methodologies/protocols and approaches on how to apply statistics over data processing for rigorous RF-EMF assessments of 5G NR mMIMO base station systems.

Traceable measurement testbed capability:

The following measurement capabilities, where applicable, incorporates the modified testbed capability developed in 14IND10 MET5G with SURREY's mMIMO testbed systems have been employed. (a) *(b)* *(c)*

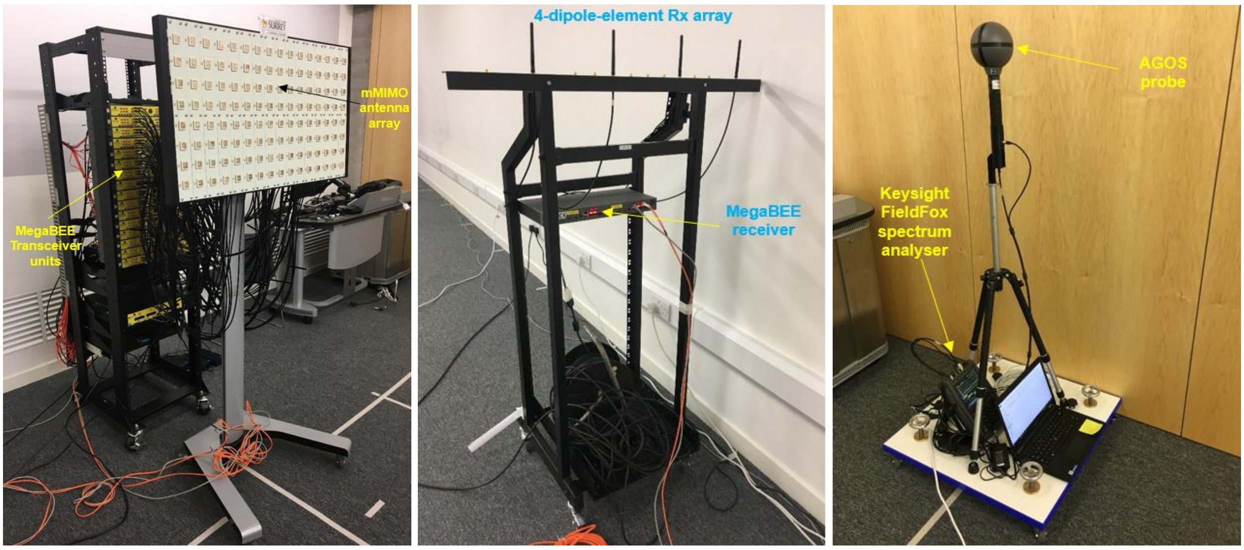
Figure 1 shows, respectively, the photos of the SURREY mMIMO beamforming system, the SURREY and Keysight RF-EMF measurement systems.

mMIMO beamforming system

The user-controllable SURREY mMIMO beamforming system comprises: 1) A BEE7 synchronization and trigger generator; 2) A MegaBEE transceiver module (each module contents four input/output RF ports and could support up to 4 channels of In-phase and Quadrature (IQ) signal); 3) A White Rabbit time distribution system; 4) A transmit antenna array with 128 (16 × 8) patch antenna elements. The mMIMO testbed can perform phase-coherent (after the over-the-air (OTA) mMIMO phase coherency calibration) and time synchronized MIMO baseband processing with user-programmable, reconfigurable and real-time signal processing field-programmable gate arrays (FPGAs)-based SDR capabilities. This testbed is capable of mimicking the performance of a realistic 5G BS and it provides flexible evaluation of various modulation schemes, new communication algorithms and protocols as well as enabling evaluation of the relevant OTA link performance.

RF-EMF measurement systems

There are two different types of RF-EMF measurement systems from SURREY and Keysight, respectively. The SURREY RF-EMF measurement system consists of up to five sets of 4-dipole-element receive antenna array each connect to a MegaBEE SDR receiver system. The Keysight RF-EMF measurement system consists of a handheld Keysight FieldFox N9917B portable spectrum analyser and an AGOS SDIA-6000 triaxial isotropic field probe. Note that the power measurement acquired by the Keysight RF-EMF measurement system will be used as a calibrated reference for the measurement campaigns.



(a) *(b)* *(c)*

Figure 1 Photos of the: (a) Surrey mMIMO beamforming system; (b) Surrey RF-EMF measurement system; (c) Keysight RF-EMF measurement system.

To achieve traceability, all these antenna and systems have been calibrated. The Keysight RF-EMF measurement system was calibrated at the NPL in its Power Flux Density (PDF) laboratory against known generated Electric field (E-field) whereas the SURREY RF-EMF measurement systems were calibrated component-wise with separate measurements made on the cables, MegaBEE receivers and antennas. The 4-dipole-element receiver antenna arrays were calibrated by using the three-antenna method. The MegaBEE receivers were calibrated for sensitivity to RF power received using power sensor.

<u>Measurement methodologies:</u>

The following shows the measurement methodologies for the indoor and outdoor measurement campaigns with SURREY mMIMO Tx system.

(i) Fixed position of Keysight and SURREY RF-EMF receivers (Rxs) distributed in the field of interest
   - mMIMO system form beam(s) randomly for different combinations of the following parameters:
     - Number of virtual active users: up to 5 (i.e., generate up to 5 beams)
     - Position of virtual active users: up to 5 (i.e., 5 beam pointing direction) between -45° and 45°
     - Data traffic pattern: Up to 5 different data rate each user (i.e., 20%, 40%, 60%, 80%, 100% resource block allocation per user)
   - Perform all traceable RF-EMF measurement using these RF-EMF receiver systems.

(ii) Change the physical position of the SURREY RF-EMF Rx system, re-run step (i), i.e., the RF-EMF measurements with random variations.

Figure 2 shows some illustrative diagrams on how virtual beamforming are formed considering the aforementioned varying factors. Note that both the Keysight and SURREY RF-EMF systems have been calibrated whereby it is envisaged that the traceable measured results could be used for cross validation. Virtual users (red dot) are not having a real receiver on that point, the beams are pre-computed and loaded/transmitted in a static way to the field of interest for the duration of the measurement. Also, the static beams are computed taking with different traffic profiles and quantity of virtual users. Also, where possible, several other varying factors that influence the RF-EMF of mMIMO system are also investigated, e.g., 1) temporal RF-EMF variation at a fixed location; 2) different line-of-sight and non-line-of-sight scenarios. Both field strength based and synchronization signal block (SSB) based RF-EMF assessment method are evaluated.

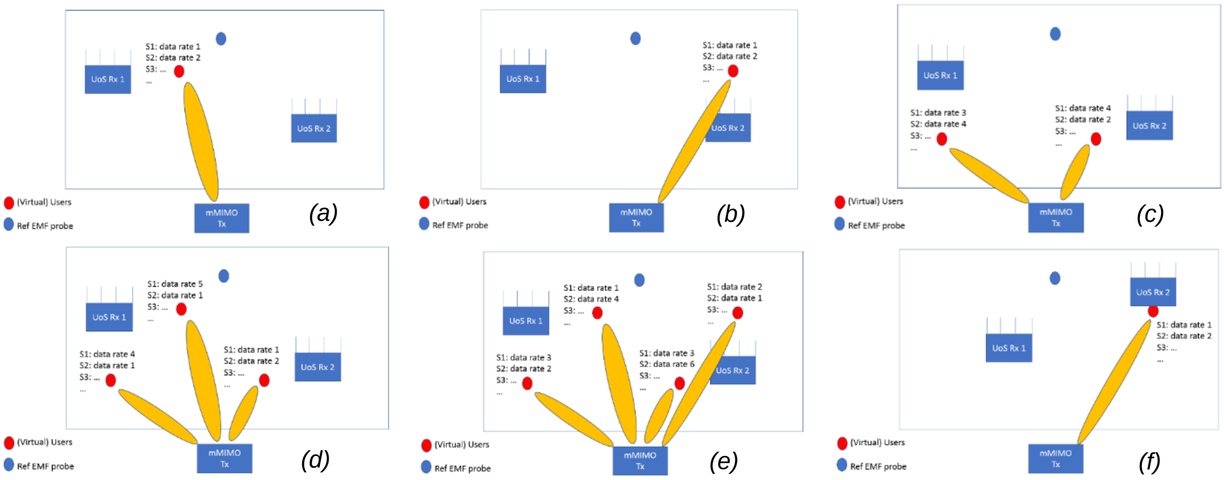


Figure 2 Illustrative diagrams showing virtual beamforming scenarios for different number of users, user data rate, and user location.

In these measurement campaigns, with specific knowledge on beam pattern, traceable the SURREY mMIMO testbed system enable insight understanding into the relevant statistics considering different number of users, user location and user data rate whereby such information would not be available for real 5G BS unless provided by the 5G BS manufacturers. In practice, to carry out realistic 5G BS RF-EMF measurement one would need to stimulate data demand from mobile user equipment (UE) terminal(s) using specific mobile applications (i.e. 'APPS') while positioning them at different practical test scenarios. A suitable statistical approach over data processing would be carried out following the measurement campaigns to try to make sensible conclusions based on observations found from the measured results obtained.

<u>Measurement campaigns:</u>

The following measurement campaigns have been carried out:

- <u>With Surrey's mMIMO system:</u> three indoor and two outdoor measurement campaigns (see photos in Figure *3*)
- <u>With a commercial 5G base station:</u> one outdoor measurement campaign (see photos in Figure *4*)

Figure 3 Photograph of the experimental setup for the SURREY mMIMO RF-EMF measurement campaign: (a) Indoor; (b) Outdoor.

Figure 4 Photograph of the experimental setup for the commercial 5G BS measurement campaign in outdoor environment: (a) map showing the 5G BS and mobile UE locations; (b) setup of mobile UE facing 5G BS.

Findings:

The relevant statistical analysis based on this experimental-based evidence has been performed to enable the insight understanding. For example, using the Keysight RF-EMF measurement probe and positioning it directly at the boresight direction of SURREY mMIMO system (i.e. at 0° position), Figure 6 shows the results of RF-EMF distribution according to the swept beam directions by using field strength method and SSB based method. By comparing both Figure 6(a) and 5(b), one observes very similar distribution pattern between these RF-EMF methods. The difference in the RF-EMF level between these two methods is envisaged due to the fact that the transmitted power for field strength-based method is not normalized whereby the transmitted power for the SSB based method is normalized. Nevertheless, one envisages that the SSB based method could be used to evaluate the RF-EMF level without going through vast data rate samples as the field strength-based method. Furthermore, Figure 6 and Figure 7 show, respectively, the relevant results and their statistics for the outdoor Surrey mMIMO measurement and the commercial 5G BS measurement.

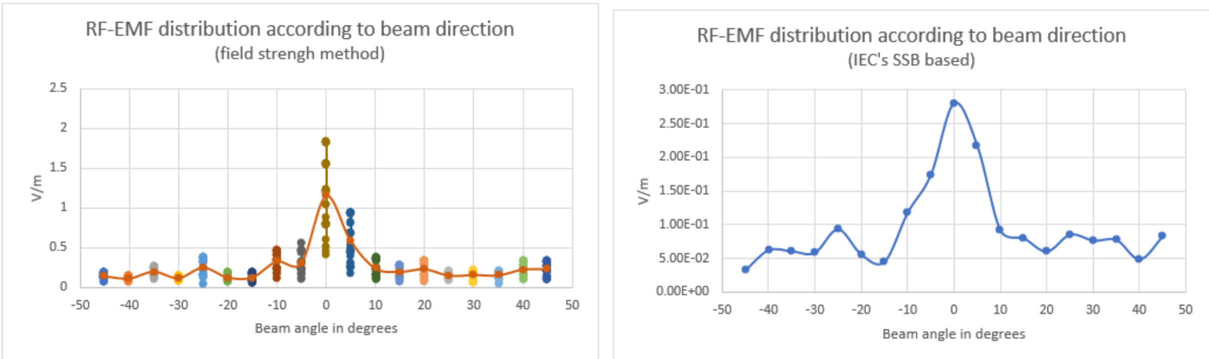


Figure 5 RF-EMF distribution according to beam point direction by using: (a) field strength method; (b) SSB method. Note that the orange line in (a) show the average of the acquired RF-EMF measurements for randomly chosen data rates at each swept beam direction.

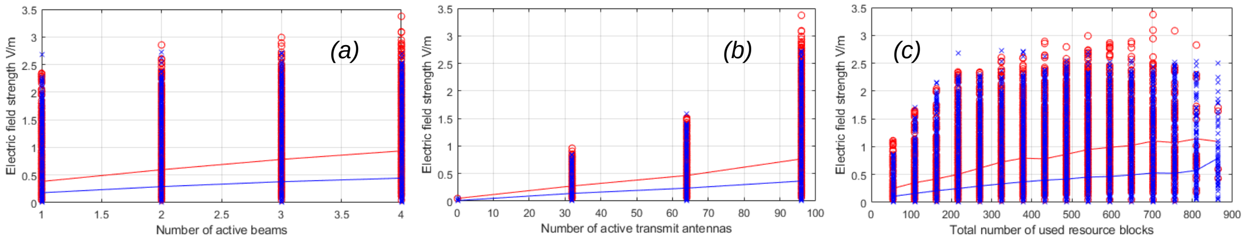


Figure 6 Surrey mMIMO outdoor measurements – Calibrated RF-EMF results and their average for different: (a) number of active beams; (b) number of active transmit antennas; (b) total number of used resource blocks.

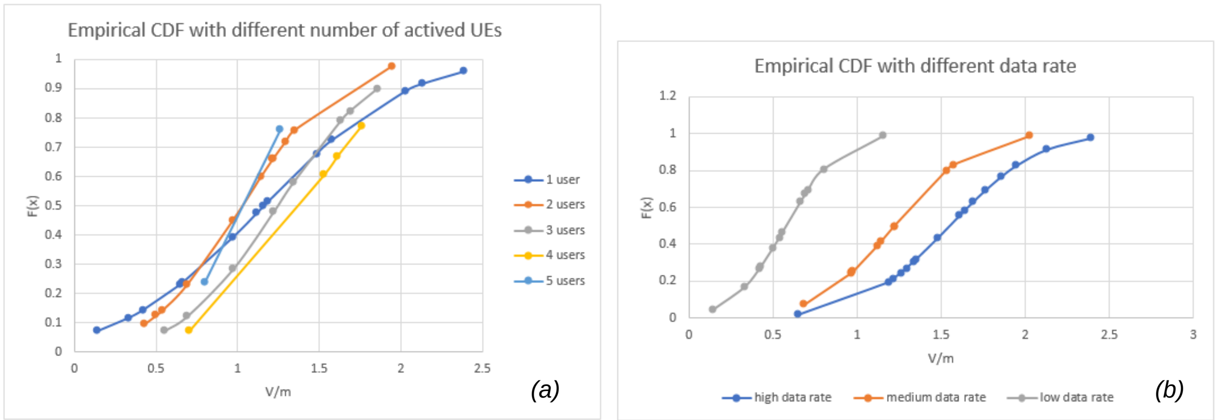


Figure 7 Commercial 5G BS outdoor measurements – CDF of RF-EMF results for different: (a) number of active mobile UE(s); (b) data rates.

Given the statistical nature of the mMIMO transmission, where the spatial pattern of transmission (i.e. number of beam used, direction of the beams) can change every few milliseconds, it makes sense that the new metrology for 5G BS is based on statistical RF-exposure models, either based on system level simulations or real measurement data acquired from deployed 5G BS. Some evidence already point out that such model provides realistic and implementable exclusion zones for 5G BSs. The outcomes of this technical objective are envisaged to enable refinement of the developed RF-EMF measurement and data processing method for 5G NR mMIMO BSs. In turn, this will form the basis of the recommendations to the technical, business and regulatory communities.

2. **To make recommendations to the technical, business and regulatory communities on how to robustly measure RF-EMF from 5G NR mMIMO BSs**

<u>Top-level achievement summary:</u>

NPL, Keysight BE and SURREY have collaborated together for the dissemination of the project outcomes. By applying the traditional approach considering the theoretical maximum transmit power in all the directions for defining the exclusion zone of 5G NR mMIMO BS would result in unrealistic large exclusion zone areas, which would prevent operators from deploying 5G BSs at sites with pre-existing third generation (3G) and fourth generation (4G) BSs. A key difference with traditional BSs is that rapid beamforming update, varying User Equipment (UE) data traffic profile and multiple user scheduling such that computing the RF-exposure of a transmission based on an average over several minutes does not make that much sense anymore. Despite on-going work on defining measurement methods and exclusion zone for 5G BS, the definition of robust and effective model and/or experimental-based methods is still being an open problem under evaluation by international organisations.

Based on empirical measurements and statistical evaluations work carried out in Objective 1 and on further empirical measurement work (for evaluating how the stringent RF-EMF limits affect 5G communications), this technical objective aims to produce RF-EMF measurement guidance for 5G beamforming mMIMO BSs and to disseminate the measured scientific evidence over the impact of current RF-EMF regulatory limits on 5G network deployment to the 5G technical, business and regulatory communities, in particular, the end users (the mobile network operators) and relevant EU regulatory bodies, to support the development of effective regulation and 5G implementation – that balances 5G performance and public safety. Such analysis is particularly relevant in certain EU Member States where the regulation is not harmonised and goes beyond international regulatory requirements in some regions, while the question of measurement methodology is relevant for all global telecommunications operators. Overall, after the work undertaken to achieve this objective, this technical objective has produced two key outputs: 1) Good Practice Guide for traceable RF-EMF measurement and data processing methods/protocols of 5G mMIMO BS and 2) an evaluation report describing how the stringent RF-EMF limits affect the 5G wireless communication performance. These outputs form the baseline recommendations on how to robustly measure RF-EMF from 5G NR mMIMO BSs. These reports (entitled 'D2' and 'D3') and the relevant measurement data could be accessed and downloaded via the following open access link – http://empir.npl.co.uk/5grfex/publications/.

A project website (http://empir.npl.co.uk/5grfex/) has been set-up, which is often being updated during the project's lifetime. At early stage of this project, the project activities and preliminary outcomes were presented to key influential EU regulatory bodies, such as OFCOM (UK), ANFR (France), etc. Their feedbacks were that the envisaged impact of this project is highly valuable and have agreed to become the project's Stakeholder Advisory Board members. Thereafter, the project partners constantly have technical discussions with Stakeholder Advisory Board to provide project progress updates and to seek for feedbacks. Also, presentations on "Metrology for 5G MIMO EMF Limits", "An Assessment of the Radio Frequency Electromagnetic Field Exposure from A Massive MIMO 5G Testbed", "A Study of Experiment-based Radio Frequency Electromagnetic Field Exposure Evidence on Stochastic Nature of A Massive MIMO System" were given at three international conferences in November 2019, June 2020, and March 2021, respectively. The target audience included key European 5G communication industry, academic and regulatory bodies that develop necessary infrastructure and regulations for 5G BSs. Furthermore, the dissemination of the project outcomes to other influential EU and international technical, business and standardisation communities, such as ICNIRP, ITU, 3GPP, ETST, CTIA, IEEE and GSMA, have been supported via project partners' wider network. This objective has been successfully completed.

Strategy and approaches:

This technical objective has been divided into three parts.

1. *Good practice guide for traceable RF-EMF measurement and data processing methods/protocols of 5G mMIMO BS system:*
   1.1. Calibration methods
   1.2. RF-EMF measurement technique recommendations
2. *Empirical evaluation on how the stringent RF-EMF limits affect the 5G communication performance*
   2.1. Measurement campaign with different test scenarios
   2.2. Evaluate the relationship between RF-EMF limits and 5G link performance
3. *Disseminations to and discussions with the technical, business and regulatory communities:*
   3.1. Stakeholder Advisory Board establishment
   3.2. A public website and international conference publications
   3.3. Dissemination to EU regulatory bodies and other influential bodies e.g. ICNIRP, ITU, 3GPP, etc.

Good Practice Guide:

This Good Practice Guide has presented the guides for traceable RF-EMF measurement and data processing methods/protocols of mMIMO systems for 5G BS applications. The hints and tips based on 'lesson learned' while carrying out the empirical measurements was also discussed. The following shows some selected highlights on the relevant calibration methods/procedures and RF-EMF measurement technique recommendations.

Calibration methods and procedures

Prior to the start of the traceable measurement campaigns, the 128-element antenna array of the mMIMO BS, 4-element mMIMO testbed receiving end (Rx) antennas, RF power for the modulated signals of the mMIMO testbed and RF-EMF measurement systems were all calibrated.

- *Multichannel OTA calibration method for mMIMO transmitting (Tx) system:*

  Given the inherent uncertainty of phase and delay caused by multiple RF channels, multi-channel calibration is a crucial factor that affects beamforming performance for a typical mMIMO antenna array. A novel OTA-based transmitter multichannel calibration method has been proposed for obtaining the RF calibration factors of multiple channels simultaneously. Figure 8 illustrates the relevant calibration procedure and a validation test result.

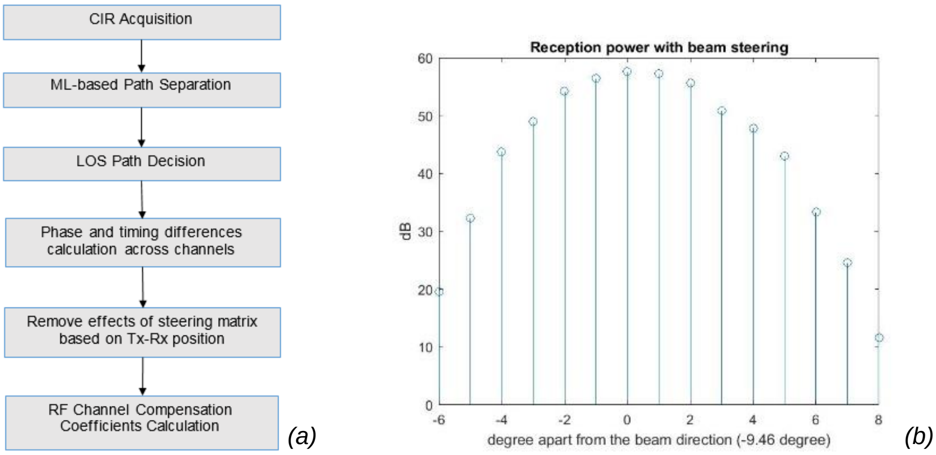


Figure 8 Multichannel OTA calibration method: (a) procedure; (b) validation test result.

- *RF-EMF receiver system calibrations:*

  The RF-EMF measurement systems were calibrated at NPL using various traceable facilities. To verify that the calibration for the RF-EMF receiver systems was producing a consistent result comparison of electric field (E-field) further measurements were carried out at NPL. Figure 9 shows the relevant setup inside the screened fully anechoic chamber facility and a validation comparison while the systems were measuring the E-field generated by transmitting a modulated signal similar waveform to those used in the main measurement campaigns. The results show that the various receive systems match well with each other and they are more or less in line with the theoretically calculated results and probe results especially at low transmit power.

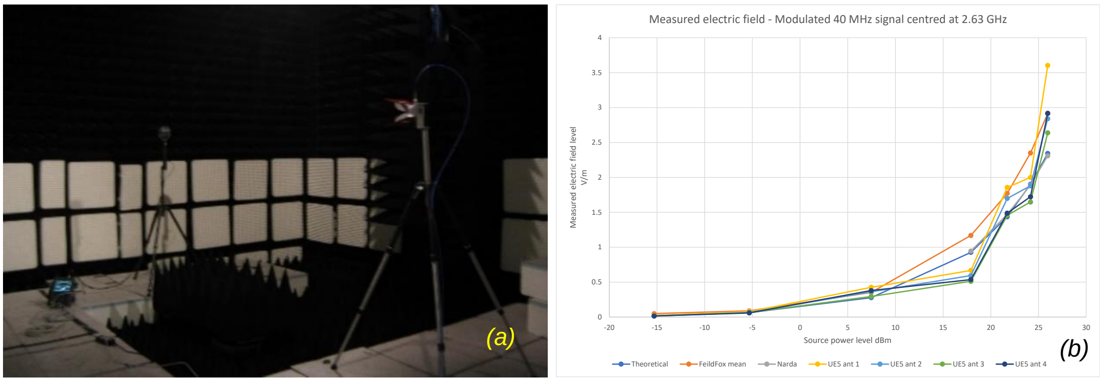


Figure 9 Multichannel OTA calibration method: (a) procedure; (b) validation test result.

<u>RF-EMF measurement technique recommendations</u>

Over the past few years, there have been a few publications discussing how to assess the RF-EMF exposure levels from 5G BS. These studies include numerical studies, and some preliminary measurements. An important problem affecting the RF-EMF measurement of 5G signals is the variation of power associated to antenna sweeping due to the sophisticated use of the space-time resources offered by the communication channel. The following shows the relevant RF-EMF measurement techniques suitable for assessment of 5G BS operation based on the RF field strength and SSB evaluations. Both these evaluations are typically based on suitable statistical approaches with the use of a field strength analyser attached to an isotropic field probe (typically, consist of three isotropic mutually orthogonal sensors).

- *Field strength method:*

  This method evaluates RF-EMF by utilising isotropic field strength probes to measure the gross receiving RF signal power in a specific frequency bandwidth and a specific time duration window no matter what sources of the RF signals are. These probes provide a vector sum of the electric or magnetic field magnitude, independent of polarization or direction of propagation of the electromagnetic wave and are traceable to national standards.

$$EMF = \sqrt{\left(E_{x_{\text{Calibrated}}}\right)^2 + \left(E_{y_{\text{Calibrated}}}\right)^2 + \left(E_{z_{\text{Calibrated}}}\right)^2}$$

where $E_{i_{\text{Calibrated}}}$ for $i = x, y, z$, are the calibrated electric field in *x*-, *y*-, & *z*-axis respectively. Note that the accurate implementation of statistical approaches/analyses to field strength-based RF-EMF assessment method relies on the insight knowledge of 5G BS operation (such as number of UEs, their spatial distribution and traffic models). i.e., if all the 5G BS operation is known (i.e., 'white box approach'), one could gain useful insight knowledge into how these varying factors affect the 5G BS RF-EMF exposure levels at each mobile UE terminal.

- *Synchronisation signal block (SSB) method:*

  In 5G, SSB consists of a block of 240 subcarriers and 4 OFDM symbols containing the Primary Synchronisation Signal (PSS), the Secondary Synchronisation Signal (SSS), the Physical Broadcast Channel (PBCH) and the PBCH Demodulation Reference Signal (PBCH DM-RS). The SSBs are grouped in block patterns called SS bursts. This method evaluates RF-EMF by measuring the RF signal power impinging into the isotropic field probe from the object BS, extracting object BS's Secondary Synchronisation Signal (SSS) from the receiving signal with the aid of the unique scrambling sequence for each BS and then assessing its Reference Signals Received power (RSRP) level. Two SSB based methodologies have been proposed, by IEC and the national metrology institute of Switzerland (METAS), respectively. There methodologies are slightly different in implementation approaches. The following shows the extrapolated maximum electric field strength, E_{asmt}, defined in IEC 62232, which is envisaged applicable for evaluation of RF-EMF for mMIMO beamforming system.

$$E_{\text{asmt}} = E_{\text{SSB}} \times \sqrt{F_{\text{ExtBeam}} \times F_{\text{BW}} \times F_{\text{PR}} \times F_{\text{TDC}}}$$

  where E_{SSB} is the field level (V/m) per RE of the SSB; F_{TDC} is the technology duty cycle; F_{PR} is the power reduction if the actual max. approach is used; F_{BW} is the total number of subcarriers within the carrier bandwidth; F_{ExtBeam} is the extrapolation factor corresponding to the ratio of the Effective Isotropic Radiated Power (EIRP) envelop of all traffic beams to the EIRP envelop of the broadcast signal at the direction to the measurement location. Figure 10 illustrates the 5G NR signal configuration and the procedure overview for evaluation of E_{asmt}.

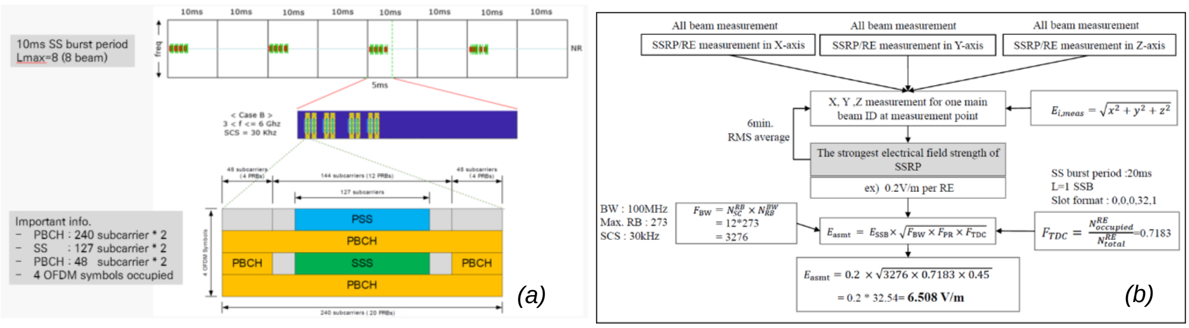


Figure 10 SSB method: (a) Configuration of the SS burst slots and SS/PBCH blocks in the 5G NR signal; (b) overview of the procedure for evaluation of E_{asmt}.

The accurate implementation of statistical approaches/analyses to SSB based RF-EMF assessment method relies on the correct demodulation and the use of suitable extrapolation technique to the measured 5G SSB RE signal under a specific 5G BS system configuration and traffic condition in the cell. i.e., no insight knowledge of 5G BS operation driven by UEs (i.e. 'black box approach') is required.

Empirical evaluation on how the stringent RF-EMF limits affect the 5G communication performance:

For the evaluation of how the stringent RF-EMF limits affect the 5G wireless communication performance, a further measurement campaign has been carried out focussing on the study of how the communication link performance between mMIMO BS and UE(s) are affected by the variation of the mMIMO BS Tx power, number of UEs, and UE data rate (by means of adjusting its MCS via modulation order and code rate). Based on the experimental-based evidence, the measurement results have been analysed to enable insight understanding. Figure 11 and Figure 12 show some selected findings for different test scenarios. Note that BLER and QAM refer to block error rate and quadrature amplitude modulation, respectively.

The results could be assessed by either looking into a fixed BLER threshold or fixed RF-EMF so to study how 5G BS could react to varying radio conditions (e.g., using a link adaptation algorithm) by changing the relevant factors, e.g., MCS, mMIMO Tx Power, etc. By varying the number of active UEs with fixed number of mMIMO Tx antennas, one observes that for the same RF-EMF level, BLER increases with higher code rate and modulation order whereby for a fixed BLER threshold, the RF-EMF also increases with higher code rate and modulation order. However, from the measured results for three to five active UEs, one observes that when using ZF precoding, the greater the number of users, the lower the quality of the beamforming hence higher BLER. By varying the number of active mMIMO Tx antennas with one active UE, one observes that for the same RF-EMF level, BLER increases with smaller number of active mMIMO Tx antennas whereby for a fixed BLER threshold, the RF-EMF level decreases with a larger number of active mMIMO Tx antennas.

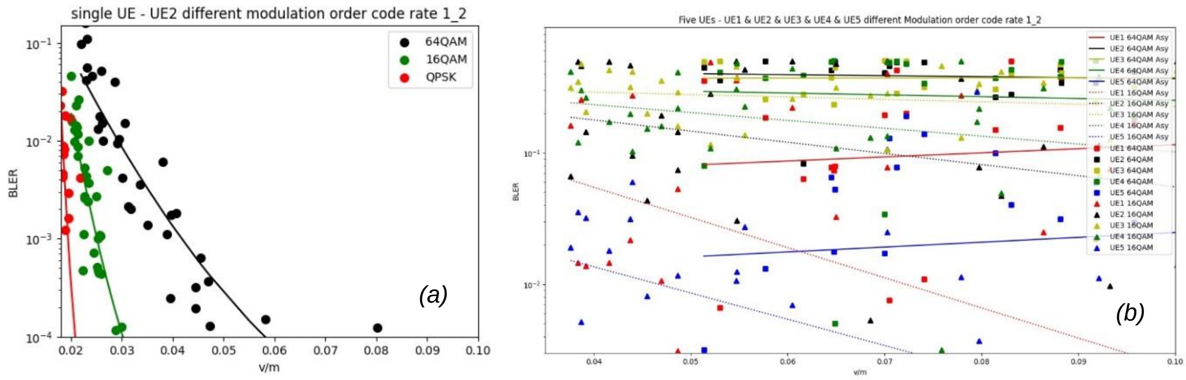


Figure 11 BLER vs RF-EMF- Comparison between different modulation order for code rate of 1/2 when: (a) one UE is activated; (b) five UEs are activated.

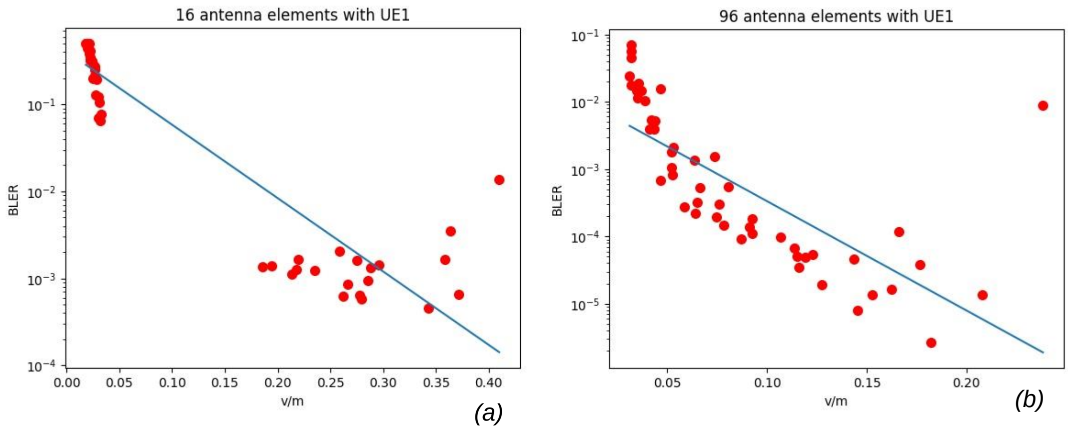


Figure 12 BLER vs RF-EMF when UE1 is activated with modulation order of 64 QAM and code rate of 1/2 for: (a) 16 mMIMO active Tx antennas; (b) 96 mMIMO active Tx antennas.

Disseminations to and discussions with the technical, business and regulatory communities:

The dissemination of this work has been accomplished through a number of channels.

Stakeholder Advisory Board

At early stage of this project, the project activities and preliminary outcomes were presented to key influential EU regulatory bodies, such as OFCOM (UK), ANFR (France), etc. Their feedbacks were that the envisaged impact of this project is highly valuable and have agreed to become the project's Stakeholder Advisory Board members. Thereafter, the project partners constantly have technical discussions with Stakeholder Advisory Board to provide project progress updates and to seek for feedbacks.

Project website and publications

A project website (http://empir.npl.co.uk/5grfex/) has been set-up with public and restricted (i.e., project partners, Primary Supporter and stakeholder only) access areas. The restricted area is being used by project partners to work on project tasks and activities through a truly collaborative approach. The public part of the website is often being updated during the project's lifetime in these four areas: project news, technical reports and good practice guides, a list of papers and a list of key contact people (from the project) and their areas of expertise. This will enable these experts to be contacted directly by end-users. Furthermore, two papers have been published in international conference proceedings and a journal paper have been submitted to a high impact factor journal.

Dissemination

Presentations on “Metrology for 5G MIMO EMF Limits”, “An Assessment of the Radio Frequency Electromagnetic Field Exposure from A Massive MIMO 5G Testbed”, “A Study of Experiment-based Radio Frequency Electromagnetic Field Exposure Evidence on Stochastic Nature of A Massive MIMO System” were given at three international conferences in November 2019, June 2020, and March 2021, respectively. The target audience included key European 5G communication industry, academic and regulatory bodies that develop necessary infrastructure and regulations for 5G BSs. Also, the partners have attended an ICNIRP meeting in April 2021 to present the results of the project and provide input to 1998 ICNIRP RF-EMF guidelines. Furthermore, the dissemination of the project outcomes to other influential EU and international technical, business and standardisation communities, such as ICNIRP, ITU, 3GPP, ETST, CTIA, IEEE and GSMA, have been supported via project partners’ wider network.

Summary and conclusions:

All the objectives have been achieved. The project has estalished a realistic, rigorous measurement capability for traceable RF-EMF measurement of 5G NR mMIMO BSs. Based on the experimental-based evidence on the stochastic nature of mMIMO operation, this project has produced specific RF-EMF exposure measurement guidance for 5G mMIMO BSs and has evaluated how the stringent RF-EMF limits affect the 5G wireless communication performance. These outputs form the baseline recommendations on how to robustly measure RF-EMF from 5G NR mMIMO BSs, which has been disseminated to influential technical, business, regulatory and standarisation communities to support the development of effective regulation and enable 5G implementation that balances performance with public safety.

5 Impact

The project website (http://empir.npl.co.uk/5grfex/) has been set-up, and contains information on the project and accessibility to the Good Practice Guide for traceable RF-EMF measurement and data processing methods/protocols of 5G mMIMO base station systems and the evaluation report describing how the stringent RF-EMF limits affect the 5G wireless communication performance.

During this project, the project members presented preliminary outcomes to key influential EU regulatory bodies, such as OFCOM (UK), ANFR (France), Swiss OFCOM, Swiss Federal Office of Environment, etc that encouraged these organisations to become Stakeholder Advisory Board members. The project team gave presentations on “Metrology for 5G MIMO EMF Limits”, “An Assessment of the Radio Frequency Electromagnetic Field Exposure from A Massive MIMO 5G Testbed”, “A Study of Experiment-based Radio Frequency Electromagnetic Field Exposure Evidence on Stochastic Nature of A Massive MIMO System” were given at three international conferences in November 2019, June 2020, and March 2021, respectively. The audience included key European 5G communication industry representatives, academic and regulatory bodies with responsibility for developing the necessary infrastructure and regulations for 5G base stations. Furthermore, the project outcomes were disseminated to other influential EU and international technical, business and standardisation communities, such as CENELEC, IEC, ITU, and IEEE and, by NPL’s wider network via METAS (Swiss’ national measurement institute), and IMTelecom (chairs the CENELEC CLC/TC 106X, active members of IEC TC 106 MT3, and IEEE ICES TC95). Two of the presentations resulted in two open access papers being published in IEEE conference proceedings.

This project has focused on the development of rigorous RF-EMF measurement techniques using the measurement capabilities that generate a known traceable EMF field and the 5G MIMO testbeds (developed under EMPIR 14IND10 MET5G) to establish a fully user-controllable mMIMO testbed. Based on the study of the experimental-based evidence on the stochastic nature of mMIMO operation, a Good Practice Guide now exists on how to measure EMF exposure from 5G mMIMO base stations in real-world conditions and provides evidence to inform discussions concerning 5G regulation with regulatory bodies. This in turn will support the safe, effective implementation of 5G. The timing of this project was ideal for 5G infrastructure development, which was planned for deployment from 2020. The project’s primary supporter, Proximus Belgium, is Belgium’s leading national operator. In Belgium, there are three separate RF-EMF regulation limits across the three regions of Brussels, Flanders and Wallonia, all of which are more stringent than the Council Recommendation 1999/519/EC based on ICNIRP guidelines. These more onerous local RF-EMF limit restrictions have resulted in Proximus’s business being impacted. The outputs from this project now enable mobile network operators to inform the European Commission on the need for harmonisation RF-EMF exposure limit policies based on international guidelines and the rigorous RF-EMF exposure measurement methods that will help industry assess 5G mMIMO base station performance more reliably in order to prove their safety to regulators. This will facilitate the adoption of evidence-based policies that will enable more effective deployment of mobile broadband and other wireless technologies.

The requirement to design mobile networks in compliance with more restrictive RF-EMF exposure limits results in less flexibility in network deployment. Network operators, in order to respect stricter limits, have to reduce the output power of their antennas. Such reduction affects coverage and creates gaps in the network, which then affects the quality of the service provided to consumers. This project has developed rigorous RF-EMF exposure measurement methods that will help industry assess 5G mMIMO base stations performance more reliably in order to prove their safety to regulators. Furthermore, this project focused on areas where 5G is subject to complex scenarios and/or technologies, or, where it is in an early stage of development, such as mMIMO. The outputs from this SIP support industry end users (mobile network operators) by providing scientific evidence to enable them to better influence policy discussions and future regulatory decisions concerning 5G regulation with EU, international and local regulatory bodies to support effective 5G implementation – that balances 5G performance and public safety.

The advantages of 5G and emerging wireless technologies will extend well beyond telecommunications and is increasingly underpinning all aspects of social and business activities. The growing demand for high-speed communication for a wide range of new applications such as autonomous driving, artificial intelligence, remote surgery and 3D holographic display, has driven the European Digital Agenda to speed up on the need to better exploit Information and Communication Technologies (ICTs) in order to foster innovation in emerging wireless technologies and economic growth. Information handling services (IHS) economics have estimated that the 5G networks and beyond will enable USD12.3 trillion of global economic output in 2035. The European Commission estimates that almost 100 million students, more than 70 million workers, almost 2 million doctors and more than 2.5 million patients in hospitals across EU will benefit directly from the emerging wireless technologies with much faster data transfer speeds by 2025.

For the European citizen, 5G and emerging wireless technologies are envisaged to provide a universal communication environment that enables us to address the wider societal challenges, such as transport, automotive, safety, employment, health, environment, energy, manufacturing and food production. By underpinning the 5G deployment with sound metrology, this project will help satisfy the EU citizen's demand for more and better data, providing huge societal benefit. Furthermore, fast reliable high bandwidth communications will change the way in which we interact with the medical and social services e.g. 24/7 monitoring of Dementia patients in their own homes. This project has disseminated the project outcomes to influential technical, business, regulatory and standardisation communities via project partners' wider network.

6 List of publications

1. T. H. Loh, F. Heliot, D. Cheadle and T. Fielder, "An Assessment of the Radio Frequency Electromagnetic Field Exposure from A Massive MIMO 5G Testbed," the 14th European Conference on Antennas and Propagation (EuCAP 2020), Copenhagen, Denmark, 15 – 20 Mar. 2020, pp. 1-5.http://dx.doi.org/10.23919/EuCAP48036.2020.9135291;https://arxiv.org/pdf/2112.09637
2. T. H. Loh, D. Cheadle, F. Heliot, A. Sunday, and M. Dieudonne, "A Study of Experiment-based Radio Frequency Electromagnetic Field Exposure Evidence on Stochastic Nature of A Massive MIMO System", the 15th European Conference on Antennas and Propagation (EuCAP 2021), Düsseldorf, Germany, 22 – 26 Mar. 2021, pp. 1-5. https://doi.org/10.23919/EuCAP51087.2021.9411325; https://arxiv.org/abs/2008.04345

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

7 Contact details

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