Publishable Summary for 16NRM07 Vector SAR
SAR measurement using vector probes

Overview

Specific absorption rate (SAR) is a measure of the rate at which energy is absorbed by the human body when exposed to a radio frequency electromagnetic field (EMF) and must be evaluated during the production of smartphones. The aim of this project was to provide the methods, software tools and datasets required for traceable calibration and uncertainty analysis of vector probe array systems (array of vector probes that automatically determines the 3D electromagnetic field mapping using amplitude and phase information through a 3D reconstruction algorithm), to measure the SAR of emitting mobile telecommunication devices. This work contributed to the international standard IEC 62209-3 and enabled the full-compliance of mobile telecommunication devices against IEC 62209-3 in terms of EMF exposure limits with better testing reliability, enabling testing times to be reduced, benefiting the telecommunications industry.

Need

Prior to the start of this project, the development of mobile phones was ever-increasing and approximately 1.3 billion smartphones were sold worldwide in 2014. In addition, the number of telecommunication protocols that need to be tested to assess SAR during the production of such smartphones has increased over the last decade. Therefore the methods included in the international standard IEC/IEEE 62209-1528 require excessively long testing times to assess compliance with SAR restrictions. For example, a modern smartphone with more than 30 transmission technologies/bands embedded would require five weeks of continuous testing to demonstrate compliance with SAR limits using the diode probe and robot specified in IEC/IEEE 62209-1528. In addition, not all foreseeable usage configurations are tested, e.g. the display of the phone is not facing towards the user and separation distances are shorter than that specified in the user manual. Furthermore, recent and upcoming communication standards, such as LTE Releases 10 and above, and 5G NR FR1, incorporate complex multiple-input multiple-output (MIMO) antennas that cannot be efficiently assessed using the systems specified in these standards, as these systems do not allow for electric field phase to be measured. Multi frequency measurement is also a challenge for traditional SAR measurement technologies as none of them have the capability to distinguish between frequency contributions to SAR. To overcome these problems, new SAR measurement systems have been developed which use arrays of vector probes, also called time-domain sensors, i.e. sensors which measure phase and amplitude to “image” the fields in a sealed phantom, a shell representing the human body, filled with a tissue-simulating liquid. Using this approach, the time required to acquire data for the SAR measurement of a handset is reduced by a factor of at least 100 compared to that using a traditional single probe scanning system. However, methods for traceable calibration and well quantified uncertainty estimates for these new systems were necessary, and were taken forward by this research before they can be adopted into documentary standards.

Objectives

The overall objective of this project was to provide the essential methods, software, data and validation required for the successful completion of the international standard IEC 62209-3 related to the measurement of SAR from handheld wireless telecommunications devices using vector based systems.

The specific objectives are to:

1. Develop traceable methods for the calibration of time-domain probes and probe arrays up to 6 GHz. In addition to verify the accuracy of such measurement systems after calibration and to determine the properties of associated sealed phantoms.
2. Establish methods for uncertainty propagation through multivariate models, using the principles given in the ‘Guide to the expression of uncertainty in measurement’ (GUM). This will include identifying the sources of measurement uncertainties and their propagation through multivariate transformations for single vector probe systems and vector probe array systems.

3. Verify the reliability of measurement systems for a wide range of transmitter types and improve the measurement of telecommunication signals and SAR measurement for a wide range of device types. This will include the development of improved data processing used with time-domain probes.
4. Develop test protocols for MIMO devices using vector probe arrays in order to determine the maximum SAR value (worst case) by combining MIMO signal figures.
5. Facilitate the uptake of the developed measurement systems and contribute to the standards development work of the technical committee IEC - TC 106 on the successful adoption of IEC 62209-3 standard vector-based SAR measurement systems in Europe. In addition, to ensure that the outputs of the project are aligned with the needs of IEC - TC 106 and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art

Methods for the calibration of single vector probes and vector probe arrays
This project went beyond the state of the art by proposing a new calibration technique to address properly the regulatory issues encountered with probe array systems when measuring devices having a radiation field different from that used for the validation. A calibration method was defined allowing the traceability of the electric field itself at the measurement points of the arrays rather than the 1 g SAR and 10 g SAR of a reference antenna. The present project was able to establish traceability through a single vector probe by its calibration in terms of a) amplitude, using the traditional analytical field in a waveguide and b) phase, using a calibrated vector network analyser. A monitoring method for dielectric properties of sealed phantom commonly used in probe array systems was also defined.

Methods for uncertainty propagation through multivariate models
This project went beyond the state of the art by providing a method for the derivation of uncertainties using the developed calibration method based on electric field magnitude and phase distributions from real-world devices in the head and body phantoms and stage by stage calibration of each single sensor sub-systems in the vector probe array. Software tools to model the propagation of errors through complex algorithms were developed in order to relate the individual sensor uncertainties to the uncertainty in the 1 g or 10 g averaged SAR for a given field excitation.

Reliability of measurement systems and improvement of the measurement of telecommunication signals and SAR measurement
This project went beyond the state of the art by investigating the reliability of vector probe array systems for measuring SAR from real-world devices i.e. source antennas of mobile phones. A set of measurands were defined describing the complex field distributions on a 2D plane resulting from a given DUT, and its similarity to other distributions. The measurement of different signal protocols, taking the effect of signal modulation and separation distance into account were analysed, and the results of the computed field distributions were compared and validated.

Testing of MIMO devices using vector probe arrays
Work performed in this project has provided the evaluation of a method for determining accurately the spatial peak 1 g or 10 g SAR from MIMO devices using vector probe arrays. The method also provides a report on the reliability of the measurement when using vector probe arrays and post processing combination of the electric field.

Results

Methods for the calibration of single vector probes and vector probe arrays

The aim of the project was to develop a method and uncertainty budget for the in-situ calibration of sensors in a vector probe array, which establishes the traceability of the amplitude and phase of the electric field itself at the measurement points of the array. A method has been devised for transferring the calibration from one antenna to another of the same type using an array system as the measurement device. The project designed a phantom prototype and a coaxial sensor, and the monitoring of the dielectric properties of the tissue-simulating liquid in sealed phantoms typically used with vector probe arrays was demonstrated. The designed calibration process enables the complex permittivity of the phantom to be measured to approximately 5% (k=2). The calibration of an electro-optic probe manufactured by the project was carried out and validated using a classical waveguide calibration system for the E-field amplitude and a vector network analyser for the phase. Reference antennas have been selected and fabricated, and corresponding datasets were evaluated by computer simulations regarding the magnitude and phase of the field distributions. By producing this methodology, the project established reference datasets from real-world devices in head and body phantoms, improving the current partial data to 1 g and 10 g SAR values from validation sources (1 g and 10 g are averaging volumes of 1 cm^3 and 10 cm^3 of tissue, respectively, with a standardised head medium density of 1000 kg/m^3) achieving our objective at two of the three frequencies initially selected with revised uncertainties, and publishing the results in a peer-reviewed journal.

Methods for uncertainty propagation through multivariate models

This project developed theory and software tools to model the propagation of errors through complex algorithms in order to relate the individual sensor uncertainties to the uncertainty in the 1 g or 10 g averaged SAR for a given field excitation. At present no such approach has been developed for these systems, and the approach of the GUM cannot be applied readily. A model was produced allowing the peak SAR to be calculated for a generalised measurement system based on a probe array contained within a phantom. This model accounts for typical interactions between the probes of the array, where the aim is to insure traceability of uncertainty components to the already established relevant parameters such as the field magnitude calibration of an optical probe in a waveguide, the vector field calibration of a reference antenna through radiated field measured by the calibrated optical probe and the vector field array system calibration while measuring the field radiated field from the calibrated reference antenna. Developed algorithms are available to the community as open source software and shared with stakeholders achieving our objective and publishing the results in a peer-reviewed journal.

Reliability of measurement systems and improvement of the measurement of telecommunication signals and SAR measurement

Validation antennas were defined and qualified and validation measurements were carried out using vector optical probes from two manufacturers, one of them being a project partner. This led to the definition of a test protocol to describe the complex field distributions on a 2D plane, resulting from a device under test (DUT), and to verify the reliability of measurement systems. Reference sources were produced and distributed to emulate real devices under test, and the developed procedure allows comparing the field from a DUT with the reference sources. Finally, three types of comparisons were performed to achieve the verification of the reliability of vector probe array systems for SAR measurement: first with a traditional scanning system fully compliant with the initial SAR measurement standard (IEC/IEEE 62209-1528), second with standard IEC/IEEE 62704-1 compliant simulated SAR target values, and third an inter-laboratory comparison involving a National Metrology Institute achieving our objective.

Test protocols for MIMO devices using vector probe arrays

New and efficient procedures for the evaluation of the true exposure level, quantified by the SAR level, were developed for MIMO devices operating beamforming. These developed procedures enable higher margin while minimizing the radiation and performance of such MIMO devices. This is in contrast when compared to traditional conservative SAR evaluation using the unpractical testing of all antenna-array states of the device with systems that do not use the phase information and are less applicable to beam-forming systems such as MIMO antennas. Improved procedures were developed for representative scenarios such as the case of MIMO devices that implement fast antenna switching by using vector based SAR measurement systems function and the case of MIMO devices that use slow varying relative phases and simultaneous equal amplitude excitations, achieving our objective and publishing the results in national and international conferences.

Impact

The project formed a stakeholder committee of nine members from mobile phone and other communications technologies manufacturers, and research organisations. Most of these members participated in the standardisation process together with consortium partners and therefore dissemination on the progress of the project was made easier. Nine presentations have been given in international and national conferences. Three open access proceedings papers and three peer-reviewed papers were published in international journals. The consortium was also able to organise i) an interactive online training course for Industry members, ii) one to one training among consortium partners to share knowledge on E-field calibration and isotropy/directivity and linearity characterisation, and iii) a workshop on SAR Best Practices Seminar.

Impact on industrial and other user communities

This project will enable manufacturers of vector-based SAR measurement equipment to have better quality control of their products and will provide greater confidence in their measurement accuracy. The consortium included two of these manufacturers (ART-FI and KAPTEOS) and other manufacturers of these systems were encouraged to join the stakeholder committee and collaboration was set up with an alternative manufacturer. A Skype training course dedicated to industry members was provided in conjunction with a standardisation TC meeting. Moreover, a secondment was arranged between NPL and KAPTEOS where KAPTEOS personnel could use NPL facilities and gain expertise in E-field calibration, isotropy/directivity and linearity characterisation. The result was the validation of the KAPTEOS vector probes in terms of performances at NMI level. The wider impact to industry will be achieved by the incorporation of the results into future revisions of IEC 62209-3 standard, which will enable to improve reliability in the use of these systems by test houses for testing full compliance of mobile telecoms devices against exposure limits. This will result in considerable cost savings for device manufacturers and will reduce the time to bring new products to market. This will also reduce the significant costs associated with the annual calibration of the validation antenna set by around 75% compared with existing methods in the standard, so offers significant advantage to the users of these systems. It will also increase public confidence on the safety of the devices.

Impact on the metrology and scientific communities

The outputs of the project will enhance the partners’ knowledge of metrology for EMF safety and of the statistical analysis of vector-based SAR measurement systems, leading to further metrological advances in these areas. Results were shared with the wider scientific community through presentations at international conferences, and an opportunity was taken at one of these conferences to hold a booth and present a poster in a dedicated session where several stakeholders from Europe and worldwide have been approached and informed on the status of the project regarding the IEC 62209-3 standard. The project’s results have also been presented to CCEM-GTRF and EURAMET TC-EM RF&MW. These two subcommittees report then to CIPM-CCEM and EURAMET-TC-EM committees. Full open access was provided to datasets, software tools and documentary reports. The project website and other databases, e.g. the partners’ websites, will be used as platforms to facilitate new scientific studies in this and related areas.

Impact on relevant standards

This project will be crucial for future revisions of the IEC 62209-3 standard by providing the required calibration and uncertainty analysis methods and text. The partners liaised with IEC - TC 106, in particular with the IEC - TC 106/PT 62209-3. Several partners are part of this working group, which have been developing the IEC 62209-3 standard to disseminate the outputs of this project and seek feedback, so that they can be incorporated into future revisions of this standard. Results were shared with IEC TC106 ‘Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure’, in particular i) MT1 (responsible for the maintenance of IEC 62209-1), ii) MT3 (responsible for the maintenance of IEC 62232), iii) PT 62704-4 ‘Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body from Wireless Communications Devices, 30 MHz - 6 GHz - Part 1:General Requirements for using the Finite-Difference Time-Domain (FDTD) Method for SAR Calculations’ and iv) JWG13 (responsible for IEC/IEEE 62209-1528 ED1 Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-worn wireless communication devices - Part 1528: Human models, instrumentation and procedures (Frequency range of 4 MHz to 10 GHz). Additionally, the project has been presented to CENELEC TC 106X ‘Electromagnetic fields in the human environment’. Final results such as written reports and guides that are suitable for adoption into the standards will be implemented through dissemination to the wider IEC - TC 106 committee to facilitate the development of standards on EMF safety of other devices and the development of standards in support of 5G, which is a stated priority of the IEC - TC 106.

Longer-term economic, social and environmental impacts

This project will ensure that 5G device compliance with safety limits for EMF can be demonstrated, which is an essential step in the implementation of this new technology. This will help i) to move towards a harmonised set of standards for assessing SAR from wireless devices, ii) to allow a dramatic cost reduction of bringing new LTE smartphone models to market thanks to reduction in the measurement time from a few weeks with a single probe to a few hours with a vector probe array and iii) to allow reduction of global power consumption thanks to efficient strategies for assessing SAR from MIMO and beamforming technologies.

This work will also facilitate the introduction of MIMO, LTE 4G, 5G and IoT devices by ensuring that their EMF safety can be assessed, in line with the increasing demands of users for network data capacity.

List of publications

D. Allal, “EMPIR European project for validation of vector array SAR measurement systems”, 19th International Congress of Metrology, Paris, 2019, https://doi.org/10.1051/metrology/201902003

L. Aberbour, “Efficient Experimental Assessment of the Specific Absorption Rate (SAR) induced by MIMO Wireless Communication Devices; Application of Vector Near-Field Measurement System”, 2018 IEEE Conference on Antenna Measurements & Applications (CAMA), https://hal.archives-ouvertes.fr/hal-02376333

Liu, Z.; Allal, D.; Cox, M.; Wiart, J. Discrepancies of Measured SAR between Traditional and Fast Measuring Systems. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2111, https://doi.org/10.3390/ijerph17062111

Gregory, A.P.; Quéléver, K.; Allal, D.; Jawad, O. Validation of a Broadband Tissue-Equivalent Liquid for SAR Measurement and Monitoring of Its Dielectric Properties for Use in a Sealed Phantom. *Sensors* **2020**, *20*, 2956, https://doi.org/10.3390/s20102956

Liu, Z.; Allal, D.; Cox, M.; Wiart, J. Reply to “Comment on Liu et al. ‘Discrepancies of Measured SAR between Traditional and Fast Measuring Systems’ Int. J. Environ. Res. Public Health, 2020, 17, 2111”, https://doi.org/10.3390/ijerph17155355

M. Teniou, O. Jawad, S. Pannetrat and L. Aberbour, "A Fast and Rigorous Assessment of the Specific Absorption Rate (SAR) for MIMO Cellular Equipment Based on Vector Near-Field Measurements," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5, https://hal.archives-ouvertes.fr/hal-02954816

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 May 2017, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Djamel Allal, LNE Tel: +33 1 30 69 21 50 E-mail: djamel.allal@lne.fr
Project website address: http://empir.npl.co.uk/vectorsar/</td></tr>
<tr><td>Internal Funded Partners:
1. LNE, France
2. NPL, United Kingdom
3. TUBITAK, Turkey</td><td>External Funded Partners:
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5. IMTelecom, France
6. KAPTEOS, France</td><td>Unfunded Partners:</td></tr>
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