

Publishable Summary for 21NRM03 MEWS Metrology for emerging wireless standards

Overview

Complex wireless technologies underpin the Internet of Things (IoT) and fifth and sixth generation (5G and 6G) mobile networks. These 'new radio' technologies require improved underpinning normative wireless standards for their radio signals, systems, and the transmission environments used, and for the radio frequency exposures created. Current telecommunications sector challenges include a lack of accurate, fast, low-cost, and traceable methods for manufacturers to demonstrate that 5G/6G product verifications match customer specifications. This project will develop the practical and efficient measurement methods required to enable normative standards for wireless channels up to sub-THz, and for radio frequency exposure assessment to better match rapidly emerging radio technologies for 5G/6G products and system over-the-air testing.

Need

The digital economy and high bandwidth mobile communications are essential tools for wealth creation in Europe and will enable an estimated USD12.3 trillion of global economic output by 2035. As digital connectivity becomes more and more ubiquitous, and offers higher capacity, it will become the new 'lifeblood' of the digital economy and connected society with over 8.9 billion mobile subscriptions envisaged by 2025. Emerging wireless technologies with Gbps connectivity has the potential to improve communications for 100 million students, more than 70 million workers, almost 2 million doctors and more than 2.5 million patients in hospitals within the EU alone by 2025. For this to happen a robust measurement infrastructure for emerging wireless technologies needs to be developed and then incorporated into relevant normative standards, e.g. CENELEC, IEC, ETSI, and IEEE, so that telecommunications manufacturers can have confidence that ICT products meet customer specifications.

The European Digital Agenda is driving the exploitation of Information and Communication Technologies (ICTs) by fostering innovations and economic growth, with a crucial role being played by the European telecommunications industry in the development of emerging wireless technologies for IoT and 5G/6G mobile networks. The rollout of these networks and large-scale deployments of cellular IoT will lead to fundamental changes to our society, impacting not only consumer service, but also industries embarking on digital transformations. Metrology has a pivotal role to ensure product quality and end-user confidence, and ultimately to improve the competitiveness of European Industry.

With the increasing adoption of complex new radio signals and large-scale multi-antenna technologies at different radio frequency (RF) bands in emerging wireless systems, manufacturer product verifications have become very time consuming and involve complicated procedures and equipment, leading to high testing costs. International standards bodies (e.g. ETSI, 3GPP), the telecommunication industries and research communities are now actively seeking improved process control on New Radio Over the Air (NR OTA) methods (*Objective 1*). Also, sub-THz wireless radio propagation channel characterisation (*Objective 2*) is currently an active topic being studied by ITU and IEEE standard development organisations, but there is a need for real-world empirical measurement data to support this R&D advancement toward 6G definitions and new product development. Furthermore, there is no reliable method to measure the RF exposure of 5G new radio systems. Importantly, CENELEC, IEC and IEEE international standards are actively seeking improved process control for addressing the product testing time-burden issue when using current RF exposure assessment methods (*Objective 3*). Hence, there is an immediate need for NMI-level metrology research to improve measurement capabilities and to provide underpinning metrology to input to the relevant standards to support the

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European Partnership

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competitiveness of European industry. The work proposed in this project aligns with broader European visions, as outlined in the European Commission Strategy – e.g. “Digital Single Market”.

It is recognised that no single NMI has, or will have, the capability to deliver all the work in this project. Our strategy, therefore, is to bring together the EU’s leading NMIs and academics in this area to build capability across all the participants that fully aligns with stakeholder and standardisation measurement needs. This approach aligns with the European Partnership on Metrology’s goal of promoting collaborative research in the most demanding fields of industrial metrology by exceeding the current state of the art.

Objectives

The overall objective of the project is to develop practical and efficient traceable measurement and characterisation methods for use in the emerging wireless standards being developed by ETSI, CENELEC, ITU, 3GPP, IEC, IEEE and other related groups. The specific objectives of the project are:

1. To develop traceable cost-effective NR over-the-air measurements to 30 GHz for: (i) new radio over-the-air system performance evaluation of sub-6 GHz and mm-wave MIMO systems with consideration where feasible of RTS, MPAC and RC+CE based methods taking into account ETSI TR 38.827 requirements; (ii) new radio over-the-air RF parametric conformance measurements of sub-6 GHz MIMO and mm-wave massive-MIMO systems using selected power-related parameters (e.g. TRP, EIRP) with uncertainty evaluations with consideration where feasible of DFF, IFF, NF-FF, mid-field and RC methods taking into account ETSI TR 38.810 and TS 38.141-2 requirements. In addition, to evaluate the methods via international comparison exercises.
2. To characterise the complex real-world sub-THz wide-bandwidth radio propagation channel suitable for the planning of short/medium-range wireless communication and active services operating up to 750 GHz for practical realisation for 5G/6G communications by: (i) the development, and verification of three traceable channel sounding testbeds (operating up to 330 GHz, 550 GHz and 750 GHz respectively), (ii) the performance comparison of these testbeds with the results added to an open access database and (iii) the validation of the test beds via channel modelling, and potentially using novel approaches based on band stitching techniques and optical cable solutions.
3. To develop and evaluate measurement protocols to quantify RF exposure levels from 5G base stations based on measuring PD exposure and from 5G mobile phones in terms of SAR and Absorbed Power Density measurements, including traceability. This will include (i) developing a measurement methodology for measuring PD exposure levels of 5G new radio base stations for incorporation into Good Practice Guidance and for submission to, e.g. IEC 62232, and IEC 62669 for their consideration as an input to Technical Specifications and (ii) developing a standardised measurement procedure for the quantification of RF exposure in terms of SAR and Absorbed Power Density measurements of 5G new radio mobile phones suitable for submission to international standardisation bodies, e.g. CENELEC CLC/TC 106X, IEC TC106 MT3 and JWG12 for their consideration as an input to standards.
4. To contribute to the standards development work of the technical committees of the relevant standards developing organisations, e.g. CENELEC CLC/TC 106X, IEEE 802.15 SC THz, 3GPP and ETSI ISG mWT and to ensure that the outputs of the project are aligned with their measurement needs, communicate quickly to those developing the standards and to those who will use them (e.g. the telecommunications industry), and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

Efficient over-the-air testing, and RF exposure measurements of 5G new radio systems with many advanced features, is needed to efficiently and cost effectively assess complex new radio system performance and product conformance to specifications. Also, new knowledge of wide bandwidth sub-THz radio propagation channel measurements for R&D advancement towards 6G definitions and new product development is needed. This project is addressing these by building progress beyond the state of the art from previous projects that included some preliminary 4G over the air studies at sub-6 GHz and 5G new radio signals at 30 GHz, respectively.

Traceable cost-effective NR over-the-air measurements to 30 GHz (Objective 1)

The main developments to date are:

A cost-effective wireless solution using a standalone phase/amplitude control matrix has been implemented. This reduces previous cable resource requirements whilst achieving efficient high-order MIMO at sub-6 GHz.

A 5G Testbed (FR1) using 5G NR SDR and emulator on PXIe VST hardware was completed, providing a versatile SISO platform,

A demonstration of a wireless solution for mm-wave with antenna polarisation/pattern discrimination for wireless cable connection was conducted. Passive measurements showed better than 30 dB isolation.

A test zone validation algorithm using directive antennas was developed, overcoming limitations of biconical antennas and enabling 3GPP NR performance tests through a two-step method (channel measuring & synthesising).

An NR beamforming antenna array system for both sub-6 GHz and mm-wave was established. This includes the development of a wideband NR signal generation testbed for sub-6 GHz MIMO, and the integration of a controllable beamformer for mmWave mMIMO testing.

A wireless cable OTA testing solution for high-order MIMO mobile terminals was designed and developed, demonstrating its potential for standardisation of future radio device performance testing.

Traceable sub-THz wide-bandwidth radio propagation channel measurements to 750 GHz for 6G (Objective 2)

The main developments are:

Novel VNA techniques for mmWave and sub-THz (20 GHz - 750 GHz) were developed, enabling characterisation and capture of channel parameters in various environments, paving the way for improved sub-THz radio link models for 6G and beyond.

Long-range sounders were established for sub-6 GHz, mmWave, and sub-THz, contributing to long-range, high-data connections for future 6G radios.

A MIMO channel sounder has been developed at 28 GHz together with a band-stitching algorithm for extended range measurements, and an antenna-in-package solution for dynamic scenarios was demonstrated.

Cross-referenced techniques across 3 European institutes were established, demonstrating confidence in proposed metrological techniques for future standardisation of sub-THz and THz communication in next-generation networks.

Strategies to quantify RF exposure levels from 5G base stations based on measuring PD exposure and from 5G mobile phones in terms of SAR and Absorbed Power Density measurements (Objective 3)

The main developments are:

An algorithm for demodulating 5G NR signals (including synchronisation PSS, SSS, and demodulation reference DM-RS) and post-processing for improved signal processing have been developed, and have shown that PSS and SSS are successfully detected.

SI traceable measurements have been carried out, demonstrating improved precision for quantifying and assessing RF exposure from 5G base stations (sub-6 GHz and mmWave).

A reference setup has been evaluated across various bands and scenarios, leveraging LTE experience and different measurement protocols and scenarios for assessing RF exposure from 5G base stations have been defined.

Machine learning models have been developed for probe linearisation, and implementation of Absorbed Power Density (APD) calibration and its validation at specific frequencies and release of first APD measurement system (24-30 GHz) enabling compliance testing with new APD limits.

Outcomes and impact

The consortium has participated in, and in some cases presented the project's activities at, seven meetings of technical committees or working groups of European and international standards organisations, and has even

contributed to IEC TC 106 APD, ETSI ISG THz and ITU THz and Wireless technology standards documents. Progress results have been presented at various conferences and workshops. Six peer-reviewed open access papers were published. Other actions included the creation of a website, a flyer, a LinkedIn group (with 19 views/members), a periodic newsletter with the first issue sent in December 2023, and the organisation of 4 convened sessions and a dedicated workshop at the 18th European Conference on Antennas and Propagation EuCAP2024. In addition, a Technical and Stakeholder Advisory Group has been set up, with 16 members already, and a collaboration with an SME has been initiated. Finally, initial KERs have been identified and a plan for their follow-up has been drawn up.

Outcomes for industrial and other user communities

This project will enable efficient, accurate and traceable measurements covering all aspects from the new radio signals, systems, antennas, propagation environments and public exposure at a wide range of frequencies up to sub-THz. This will have direct outcomes on wireless communications and electronics industries by ensuring product quality and end-user confidence. Notable examples include virtual and augmented reality, autonomous driving, remote surgery, artificial intelligence, smart manufacturing, unmanned aerial vehicles (UAV), IoT and vehicle-to-everything.

The establishment of measurement traceability and the improvement of measurement accuracy will enable manufacturers to provide confidence in their specifications. This plays a key role in the customer/supplier relationships, for which products need to be demonstrated as 'meeting specification', regardless of who is carrying out the test or when/where the test is being performed. The outcomes of this project will allow emerging wireless product manufacturers to specify their products more precisely, leading to systems with better performance. This in turn will boost the product yields for the manufacturers and potentially reduce prices for customers as well as enhancing user experiences.

This project will achieve new measurement capabilities by extending the current capabilities of the participating NMIs, to 750 GHz for radio propagation, to 30 GHz for new radio over-the-air measurements and to 40 GHz for new radio RF exposure measurements. This will lead to greatly improved access to, and dissemination of, measurement traceability for European NMIs, accredited testing and calibration laboratories and the manufacturers of test instrumentation. This will be beneficial for all end-users, including customers and suppliers of emerging wireless devices and systems.

The project has designed and implemented a new traceable calibration concept for APD probes and produced a new generation of APD probes for near-field measurements for the millimetre-wave range that will pave the way to future uptake by manufacturers and testing laboratories in the telecommunications field. This contributed to the release of the first APD measurement system.

Outcomes for the metrology and scientific communities

This project involves five European NMIs with world-leading capabilities, along with five world-leading academic, and seven key industrial unfunded beneficiaries, who bring in their specific knowledge, and measurement instrumentation to these emerging technologies. Together these provide a strong coherent consortium that will enhance the quality of the research outputs, and this will maximise the overall outcomes from the project. The outcome will be to propose changes to NMI calibration and measurement capabilities to provide the underpinning metrology that supports the European emerging wireless technology research effort and to keep the focus within Europe. During the lifetime of this project, preparatory tasks will be undertaken to subsequently establish a coordinated network of NMIs that will provide comprehensive measurement capability based on the scientific activities in this project, and, in other earlier and current European projects (specifically, previous EMRP).

The project was presented at the International Metrology Congress and at the EURAMET TC-EM Subcommittee (SC) Radiofrequency and Microwave (RF&MW) Meeting, where representatives from several European NMIs not involved in the project expressed their interest and expectations in the project results.

Outcomes for relevant standards

The NMI-level metrology research performed in this project, will provide the underpinning metrology as input to the relevant standards in this area in order to support the competitiveness of European industry. The project outcomes will enable standard bodies to implement practical and the efficient measurement methods required to enable normative standards to better match rapidly emerging radio technologies, which was not previously

possible. This project will make substantial contributions to the following international standards and related documents:

- (i) International standards developed by ETSI/3GPP: TS 38.141-2, TS 38.151, TS 38.161, TS 38.521-1, TS 521-2, TS 521-4
- (ii) International standards developed by IEEE: IEEE 802.15.3d, IEEE 1720
- (iii) International standards developed by IEC: IEC TC106 MT3 and JWG12
- (iv) International standards developed by CENELEC: CLC/TC 106X
- (v) International standards developed by ITU: ITU-R IMT-2020, ITU-R SM.2352, ITU-T SG5

This project will also have indirect outcomes on the European standards being developed by the European Telecommunications Standards Institute (ETSI) through 3GPP. These include 3GPP TR 38.827, 3GPP TR 38.810, 3GPP TR 37.842, 3GPP TS 38.101-1, 3GPP TS 38.101-2, 3GPP TS 38.101-4, 3GPP TS 38.104, 3GPP TS 38.141-2, ETSI EN 302 686 and ETSI EN 302 550. Progress and output from this project will be disseminated to the above standards bodies and committees, via representatives in the consortium who are involved in these standards bodies.

The project partners involved in technical committees and working groups of international and European standards development organisations, such as ETSI, IEEE and ITU, have already contributed to the development of new or existing standards documents, promising potential exploitation of the project results. To date the results achieved by this project relating to APD probe calibration (Objective 3) have been included in the IEC TC 106 JWG12 draft technical report "Evaluation of Absorbed Power Density Related to Human Exposure to Radio Frequency Fields from Wireless Communication Devices Operating between 6 GHz and 300 GHz".

Longer-term economic, social and environmental impacts

Economic: The digital economy, and high bandwidth mobile communication, are essential tools for wealth creation in Europe. Digitisation of products and services has a significant economic impact, with more than 110 B€ extra revenue added to industry per year in Europe. To date, over 80 % of Europeans have a mobile phone and 50 % a smartphone. 315 million Europeans use the internet every day. These figures are constantly growing and have been illustrated by a demand-led compound data growth rate of 40 % per year. The measurement science generated by this project will pave the way for the development of emerging applications using the future generation wireless network including virtual and augmented reality, autonomous driving, remote surgery, smart manufacturing, UAV, IoT, Vehicle-to-Everything and security imaging. This will enable European businesses to move into these areas with confidence and it will ensure a strong competitive advantage over organisations outside the European region, and it will attract business from global markets.

Health and Social Care: The impact of emerging wireless technologies will extend well beyond telecommunications, and it is increasingly underpinning all aspects of health and social care activities. This will lead to fundamental changes to our society, impacting not only consumer service, but also industries embarking on digital transformations. It is 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. Furthermore, rigorous scientific evidence on RF exposure issues will enable effective wireless system deployment to be supported that balances user experience and public safety.

Environment: Space radiometers play a key role in Earth monitoring, which provides information about global climate change and weather forecasting. This project will facilitate more accurate and traceable measurements at millimetre-wave and terahertz frequencies, yielding radiometers with better performance. The energy efficiency of systems will also be improved as a result of more accurate measurements. The average electromagnetic radiation intensity has been steadily increasing, fuelled by the evolution of wireless communications for applications like IoT, 5G and beyond. To reduce the impact of electromagnetic fields on the environment, it is therefore important to decrease the transmitted power of wireless communication systems and to measure power density as precise as possible, which this project will underpin.

The project's developments in efficient OTA measurements, sub-THz wide-bandwidth channel measurements, and RF exposure assessment, as described in the results above, are likely to drive innovation within the wireless technology industry by enabling new applications and markets. These developments may also

enhance communication, healthcare, and safety, while potentially contributing to environmental goals through improved climate monitoring and energy efficiency.

List of publications

Bengtson, M., Lyu, Y., Fan, W. (2022) 'Long-range VNA-based channel sounder: Design and measurement validation at MmWave and sub-THz frequency bands', *China Communications*, 19 p. 47-59. Available at <https://doi.org/10.23919/JCC.2022.11.004>

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Li, M. et al (2023) 'Omni-Directional Pathloss Measurement Based on Virtual Antenna Array With Directional Antennas', *IEEE Transactions on Vehicular Technology*, 72 p. 2576-2580. Available at <https://doi.org/10.1109/TVT.2022.3210399>

Lyu, Y. et al (2022) 'Design and Validation of a Multilink Phase- Compensated Long-Range Ultrawideband VNA-Based Channel Sounder', *IEEE Transactions on Microwave Theory and Techniques*, 70 p. 4528-4543. Available at <https://doi.org/10.1109/TMTT.2022.3194045>

Nielsen, J.O., Fan, W., Ji, Y. (2023) 'On Band Stitching for Wideband Vector Measurements With Vector Signal Analyzers', *IEEE Transactions on Microwave Theory and Techniques*, 71 p. 710-718. Available at <https://doi.org/10.1109/TMTT.2022.3207997>

Yuan, Z. et al (2023) 'Spatial Non-Stationary Near-Field Channel Modeling and Validation for Massive MIMO Systems', *IEEE Transactions on Antennas and Propagation*, 71 p. 921-933. Available at <https://doi.org/10.1109/TAP.2022.3218759>

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

Project start date and duration:		1 October 2022, 36 months
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Internal Beneficiaries: 1. LNE, France 2. CMI, Czechia 3. RISE, Sweden	External Beneficiaries: 4. AAU, Denmark 5. IMTelecom, France	Unfunded Beneficiaries: 6. Anritsu AU, Austria 7. Keysight BE, Belgium 8. MVG, Italy 9. NNF, France 10. ZTE AB, Sweden
Associated Partners: 11. BJTU, China, 12. CAICT, China, 13. METAS, Switzerland, 14. NPL, United Kingdom, 15. QMUL, United Kingdom, 16. SPEAG, Switzerland, 17. SURREY, United Kingdom		