Publishable Summary for 14IND10 MET5G
Metrology for 5G Communications

Overview

5G (fifth-generation) standardisation bodies and industries are facing the challenge of diverse 5G technological requirements. Metrological support is needed to underpin all aspects of 5G, including signals, devices, and systems. This project has addressed these needs by developing the traceable metrology required by 5G communications to improve the associated measurement uncertainties. This project's achievements have been disseminated to industry, academia and the standardisation bodies that develop the necessary infrastructure and standards for 5G communications. This project has produced a number of significant outcomes. Two of the more notable deliverables are firstly, the development of a millimetre wave (mm-wave) multiple-input-multiple-output (MIMO) testbed which has been used by a number of key 5G stakeholders and industries and secondly, the introduction of a new commercial non-linear device measurement service.

Need

High bandwidth mobile communication is an essential tool for wealth creation by EU citizens. This is illustrated by a demand-led compound data growth rate of *circa* 40% per year (see https://ec.europa.eu/digital-single-market/en/news/broadband-big-pipes-potential-growth). The definition of the 5G standards is in progress, with real-world deployment planned for 2020. Focusing on the user experience, the 5G network promises to deliver millisecond latency, multi-Gbps data capacity, low energy consumption and seamless connectivity between trillions of devices serving billions of people.

A raft of new technologies is anticipated to be considered for the sub-6GHz and mm-wave spectrum bands to support the anticipated, significantly increased, user density which is needed if the 5G rollout is to deliver on its stated goals. Metrology is fundamental to underpinning the success of the new technology and must consider all aspects including signals, devices and systems and is essential in the development, manufacture and deployment of 5G technologies. The overall need is to provide timely support for EU industry and academia during the development of 5G technologies.

Testing at mm-wave bands presents fresh challenges due to the increased losses, both within the system and in free-space, whereas massive-MIMO antenna system characterisation presents additional challenges that stem from the increased complexity, larger number of interfering sources and from imperfections within the substantially more complex hardware. The high density of users will mean that a critical concern will become the resilience of the system to interference arising from nearby users. The development of 5G systems is further complicated as a result of the nonlinearities introduced when developing highly efficient microwave systems. As a result of this, there is a clear requirement for the introduction of a sound definition of the Signal-to-Interference-plus-Noise-Ratio (SINR) and for the development of traceable nonlinear and MIMO measurements both below 6 GHz and at mm-wave frequencies. To meet these needs, validated test methods and a link to standards bodies, such as ETSI (the European Telecommunications Standard Institute), are required.

Objectives

The project aimed to provide EU industries and academia a competitive advantage by providing the essential underpinning metrology for their development of 5G mobile communication platforms. The tasks focused on verifying the system capacity and performance in several critical areas where the user density was high. Participation in the standardisation process was essential to maximise impact and to harmonise the test-methods. The specific objectives of the work were to:

1. **To define and develop traceable methods to measure Signal-to-Interference-plus-Noise Ratio (SINR) over a wide frequency range** – Develop definition(s) of SINR for potential 5G modulation and coding schemes and develop the relevant practical SINR traceable methods to accommodate higher areal density of interference signals
2. **To improve metrology for traceable MIMO antenna systems** – The greater number of antenna elements and operation at mm-wave frequencies will significantly increase the system test-complexity. The objective was to underpin the development of traceable test methods and algorithms so that efficient

and traceable testing is possible. A 5G mm-wave Massive-MIMO testbed was constructed that also provided a facility for remote access.

3. **To develop traceable metrology for 5G mobile communication devices** – Nonlinearity limits coexistence and ultimately the system capacity. The objective was to place nonlinear measurements, using X-parameters and S-functions onto a sound footing, supporting uncertainty relationships and model extraction parameters and proven by inter-comparison with other users worldwide. This included validation of new nonlinear test methods for application at mm-wave frequencies.
4. **To engage with industries that manufacture 5G mobile communication technology** – The measurement infrastructure developed by the project will be used to support the development of new, innovative products, demonstrating the benefit of metrology in improving the take-up of the technology and enhancing the competitiveness of EU industry.

Progress beyond the state of the art

In order to accommodate the aforementioned 5G network promises, 5G systems need to further evolve beyond the current state-of-the-art. From the metrological perspective, this project has enabled the development of the traceable metrology required by 5G communications to underpin all aspects from the signals, devices, and systems for the emerging 5G technologies. The following paragraphs present the details of the selected key 5G communications metrology areas covered by this project:

1. **To define and develop traceable methods to measure Signal-to-Interference-plus-Noise Ratio (SINR) over a wide frequency range**
   Prior to the start of this project the state-of-the-art was the use of SINR as an important metric for operators when planning their networks. Nevertheless, to date, SINR is not defined by 3GPP but by a Channel Quality Indicator. This project has progressed beyond the state-of-the-art by defining and validating new SINR definition suitable for potential 5G modulation and coding incorporating viewpoints from industry, standard and literature survey as well as devise SINR measurement methods for a range of possible future communication systems applicable to specified 5G scenarios.
2. **To improve metrology for traceable MIMO antenna systems**
   Prior to the start of this project the state-of-the-art was the methodology for over-the-air testing of MIMO for sub-6GHz. MIMO antenna system plays significant role in 5G communications. This project has progressed beyond the state-of-the-art by extending previous MIMO measurement metrological capabilities (developed under previous EMRP IND51 MORSE project) and developing new MIMO testbeds capabilities to accommodate higher areal density of interference signals and facilitate operation at mm-wave frequencies for 5G communications.
3. **To develop traceable metrology for 5G mobile communication devices**
   Prior to the start of this project the state-of-the-art was the use of RF metrology for electronic devices and components using vector network analyser. Nonlinear parameter characterisation of hardware components play an important role in achieving energy efficiency in 5G communication systems. This project has progressed beyond the state-of-the-art by extending previous RF metrological capabilities (developed under previous EMRP SIB62 HF-Circuit project) and developing new nonlinear measurement methods and simulation tools for wide-band network analyser measurement system.

Results

Test equipment is available for MIMO applications under the current 4G communications technology. However, activity within the current COST IRACON, the earlier COST IC1004 and COST 2100 illustrates that the measurement issues have not been fully resolved. This project constitutes the first metrological focused project and has enabled EU NMIs to enhance existing facilities, to develop the required capabilities for 5G antennas, signals, devices and system measurements. Additionally the results of this research and the knowledge gained has helped EU NMIs and industry to develop solutions to address 5G metrological problems which provided critical support to instrument and wireless system manufacturers.

The project has carried out inter-laboratory studies by involving and connecting industry and academia to establish a means of comparison between measurement techniques which will enable the best techniques and practices for industry to be identified and exploited. The relevant key achievements of the project with respect to the aforementioned technical objectives are:

1. **Development of traceable methods to measure Signal-to-Interference-plus-Noise Ratio (SINR) over a wide frequency range**

   SINR is an important metric for operators to use when planning their networks and has therefore, a direct bearing on running costs. SINR also underpins the pass/fail testing of user equipment, such as smart phones, having a wide reaching impact. The proposed new 5G networks cover a wider range of frequencies and so there are a number of unknown factors. As a starting point, and in parallel with studying the existing body of work in this area, a consultation process with industry was carried with the purpose of surveying whether additional definitions could or should be developed. This resulted in the production of an important survey which incorporated viewpoints from industry, standard and literature on the definitions of the SINR for potential 5G modulation and coding. New SINR definitions have been developed for a range of possible future communication systems and these have been modelled and a series of measurement configurations have been analysed to determine the trade-off between cost, complexity and accuracy. Throughout this project, several configurations for traceable single-input-single-output (SISO) and MIMO SINR simulations and experimental measurements have been performed to validate the SINR definitions. In addition to the traditional definition, the additional definitions suit adjacent channel and massive MIMO configurations have also been developed. A MIMO system was measured over the air in a campaign of traceable measurements using a mobile-phone tester and commercial user equipment (modem) with a directly connected system. Traceability to RF power was achieved using a calibrated RF vector signal analyser. The Over the air test measurements was linked to RF power levels and to data throughput. Over-The-Air measurements replaced cabled measurements and there are additional uncertainties associated with this approach. Repeated measurements showed a higher spread of the RF power. Both SISO and MIMO measurements were investigated with noise and interference signals. The directly connected measurements enabled the match results to be measured and applied to lower the measurement uncertainties. The technical insights gained from the results indicate the feasibility of using error vector magnitude (EVM) to evaluate the SINR at a device that does not know where its interferer source is and how the multipath can be exploited to make it possible to estimate the SINR for use in conformance testing reliability in massive MIMO schemes. This objective has been successfully achieved and the outcomes provide robust definitions of SINR for a range of possible future single and multiple antenna communications systems and enable development of traceable measurement strategies that simplify the measurements and industry cost.

2. **Improve metrology for traceable MIMO antenna systems**

   Supporting metrology for traceable MIMO antenna system measurements need to be further extended to accommodate higher areal density of interference signals and operation at mm-wave frequencies for 5G communications. Throughout this project, three MIMO testbeds (2 x 2 mm-wave MIMO, 8 x 2 mm-wave MIMO and 32 x 3 sub-6GHz massive MIMO) have been developed and used. The developed testbeds capabilities are critical for improving metrology for traceable MIMO system characterisations. An interface to allow the remote access of the 8 x 2 mm-wave MIMO testbed and its simulator has been developed and tested. The 2 x 2 mm-wave MIMO system is fully functional and provides a user programmable software define radio capability that enables the utilisation of various 5G candidate waveforms. Using these testbeds, several SINR measurement campaigns at mm-wave and sub 6GHz including SISO and MIMO, have been conducted with several 5G candidate waveform signals for: 1) in-band; and 2) out-of-band scenarios. Using and processing the results obtained from the SINR measurement campaigns, a detailed analysis has been performed, compared and analysed. This has enable the evaluation of the SINR based on EVM and to form a suitable SINR-EVM relation in simulation that can be adopted for use with a demonstrator. This can also be used for the evaluation of the relevant SINR definitions and to test the concepts behind the measurements. Based on the measurement findings, the SINR definition has been thoroughly reviewed. Through remote access, the 8 x 2 mm-wave MIMO testbed has been widely used by a number of key 5G stakeholders and industries. This remotely accessible system has benefit both large companies and SMEs across Europe which is of great utility when testing prototype products. A comparison between this testbed’s hardware performances and the predicted performance as provided by the simulator has also been successfully carried out. This objective has been successfully achieved. New MIMO measurement capabilities at NMIs have been developed which extended current traceable MIMO measurement metrologies to accommodate higher areal density of interference signals and facilitate operation at mm-wave frequencies.

3. **Traceable metrology of nonlinearity**

Nonlinear parameter characterisation of hardware components play an important role in achieving energy efficiency in 5G communication systems. Its measurement uncertainty quantification and computation procedures are needed. Throughout this project, useful measurement methods and simulation tools for establishing the quality of wide-band measurement systems have been developed. A new wideband mm-wave operation network analyser measurement system has been setup and measurements have been performed, for the first time, using signals with the correct waveform and statistics for 5G communication systems. The measurement uncertainty quantification and computation procedures have been developed. Also, the relevant calibration algorithm and some of the targeted simulation model components for the measurement system have been implemented. Furthermore, a new non-linear measurement campaign using a non-linear vector network analyser (NVNA) on downconverters has been carried out. The relevant measurement-based behavioural models have been extracted. The models of calibration standards, which forms part of the simulation test bench, have been created. Also, the additional background analysis on pre-distortion and multi-tone measurements were performed. An inter-comparison exercise has been successfully carried out between participating partners over several amplifiers, which operate as nonlinear devices under tests. Using different techniques, the nonlinearity of the RF amplifier has been quantified. The measurement methods and software tools that were developed has influenced how characterization of future 5G components and devices can be performed and evaluated. The result has been of use both for manufacturers of electronics and for the measurement and test labs that verify the operation of the products.

Impact

The dissemination of this work has been accomplished through a number of channels. These included giving 18 presentations at different conferences, including IEEE, EuCAP, URSI, etc., organising conference workshops, presenting training courses, hosting meetings, as well as through the publication of technical papers which have documented the work. Throughout the project the team have continued to contribute towards and participate in ETSI and IEEE standards. Also, the project team has maintained contact with the stakeholder advisory group who have held a specific role in advising on the specific standards requirements in 3GPP activities, which have driven the direction of the measurement trials to be carried out in the coming years.

The stakeholders engaged in the project represent the NMI, standardisation bodies, and industry and academia communities. Significantly, the project team has access to the majority of the relevant communication industry via two large academic-hosted 5G industry innovation centres (at The University of Surrey and Chalmers University of Technology). This has enabled industry to access and apply the knowledge gained, including new measurement services, in a timely and efficient fashion.

Impact on relevant standards

As noted above, the process for defining the 5G standard is currently in progress. The timing of this project was therefore ideal for collaborating with the ETSI, IEEE and other specification standards bodies as the relevant standards have not yet been finalised. The first 5G Non-Standalone (NSA) (which utilise the existing 4G infrastructure) network and device standard was approved by 3GPP in December 2017 where 5G Standalone (SA) network and device standard is still under review and envisaged to be signed-off by 3GPP in late 2018. To develop the necessary infrastructure and standards for 5G, standardisation bodies and worldwide research and development communities have started seeking a global consensus for the visions, applications, standards, and identification of suitable spectrums. Entry at this point will be key to acceptance of a SNIR definition and for agreement to use techniques and algorithms developed within this project. The project team have participated and contributed in ETSI meetings and established a special interest group in the development of an IEEE standard for nonlinear measurements and measurement techniques as a mechanism for input to the standards. The outcomes of the SINR definitions survey report have been presented at the 5G Innovation Centre Standards Sub-Group meeting hosted at The University of Surrey. This group provides a conduit to 3GPP and other international standards bodies and is therefore very important for maximising impact.

Impact on industrial and other user communities

The overall EU investment from 2007 to 2013 amounted to more than 600 M€ in research on future networks, half of which was allocated to wireless technologies contributing to development of 4G and beyond 4G. This project was directly relevant to these activities that are being carried out by the 5G communications industry and academia, to develop the necessary infrastructure and standards for 5G communications. The overall aim is to have 5G systems rolled-out by the year 2020 and to support EU 5G communication industry to gain a competitive edge.

A traceable measurement service of SINR has been identified as an exploitable outcome. In addition, several industry defined MIMO testbeds have been developed. This project has placed special emphasis on areas where 5G is subject to complex scenarios and/or technologies, or, where it is in an early stage of development, such as Massive MIMO and mm-wave communications. The testbed has been made remotely accessible for the project partners and for key industrial and academic stakeholders. Furthermore, through the remote access, the testbed has already been used by parties such as: Ericsson, Saab, Infineon, National Instruments, Ampleon, and Qamcom, etc. This has facilitated timely support for the EU 5G research and development effort and enabled instrument and 5G wireless system manufacturers to develop and implement new systems, minimising test and measurement costs and reducing the time to market for new products and services. Through strong collaboration within this project: 1) NPL and SURREY has established a new joint facility – the Nonlinear Microwave Measurements and Modelling Laboratories (n3m-labs) in June 2016 dedicated to nonlinear microwave measurements and modelling for the next generation of electronic devices; 2) has led to the next 2017 – 2020 EMPIR project entitled ADVENT.

Impact on the metrology and scientific communities

At present, with strong global momentum, multiple worldwide 5G research projects are focusing on new system concepts and technological enablers to break through the current limitations. Several 5G communication industry, standardisation bodies (e.g. 3GPP, ETSI, IEEE, etc.) and worldwide research and development communities (e.g. 5G-PPP, IMT-2020, 5G Americas, etc.) will face a wide variety of issues and challenges from diverse 5G technological requirements. Neither the NetWorld2020 European Technology Platform for Communications Networks and Services – joint white paper on 5G nor the cluster of EU projects in the Radio Access and Spectrum area address the metrology requirements to ensure that 5G meets the stringent specifications set out by the Networld2020 white paper. Under the 7th Framework Programme for Research and Technological Development (FP7), the EU Commission has already launched more than 10 projects to explore the technological options available leading to the future generation communications, adding up to over €50m for research on 5G technologies with a view to having deployable systems by 2020. The FP7 projects do not include metrology objectives either. These EU research projects address the architecture and functionality needs for 5G networks.

For the first time in the world metrology activities are being carried out in this project before the roll out of 5G communications. This project has put metrology for 5G communications at the heart of the research and focused on the development of three important inter-linked metrological capabilities for 5G mobile communication technologies, namely: traceable SINR, MIMO, and non-linear measurement to cover the signal, component, and system levels. The main impact of this project has directly affect the definition of 5G technologies through the inclusion of new methods and means.

Standardisation and testing in the areas of 5G and mm-waves are considered to be ETSI and 3GPP core business and they are interested in this collaborative project concerning measurement for 5G issues. The impact has been assured by the participation of three NMIs, two world-class 5G research institutes (with large industry fan-out), and two industrial partners. The project has submitted several documents to the COST IRACON and standards organisations (ETSI, 3GPP, CTIA, and IEEE). Additionally, the EURAMET Technical Committee for Electromagnetics has been briefed during its annual meeting about the progress achieved in the project.

Longer-term economic, social and environmental impacts

Communications have a significant longer-term economic impact with 50% of economic growth in the European Union driven by ICT (Information and communication technology). Currently, the industry ensures 1.3 million EU jobs, representing a mobile telecommunication economy of 160 bn€ (see http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/ict-14-2014.html).

The measurement methods developed from this project will help industry assess 5G system performance more reliably thereby giving EU industry a significant competitive advantage over global communications manufacturers.

Generally users blame poor performance of their equipment on the network operator but in many cases the fault lies with the sensitivity of the user equipment. By underpinning the 5G evolution with sound metrology,

this project will help satisfy the EU citizen's demand and improve the quality of the user experience for more and better data, providing huge societal impact.
The ever increasing demand for wireless communication increases the importance of energy efficiency in mobile communication systems. The Networld2020 whitepaper states that the "energy efficiency (90 % less consumption for the same service compared to 2010 levels), coverage (global and seamless experience), battery lifetime (10x longer)". This project will provide traceable measurements that help manufacturers reach the energy efficiency requirements.
This project has resulted in new SINR definitions, MIMO measurement testbeds & capabilities, and commercial non-linear device measurement services to support the next generation wireless systems, leading to potential financial saving, societal and environmental benefits being realised by the 5G industry and user communities.

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Project start date and duration:	01 May 2015, 36 months	
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Internal Funded Partners: Partner 1 NPL, UK Partner 2 CMI, Czech Republic Partner 3 RISE, Sweden	External Funded Partners: Partner 4 Chalmers, Sweden Partner 5 SURREY, UK	Unfunded Partners: Partner 6 Anritsu, UK Partner 7 Keysight DK, Denmark