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1 Executive summary

Introduction

5G (fifth-generation) standardisation bodies and industries are facing the challenge of diverse 5G technological requirements. Metrological supports are needed to underpin all aspects of 5G, including signals, devices, and systems. This is the first world leading metrological focus project that has addressed these needs by developing the traceable metrology required by 5G communications to provide timely support for EU industry and academia during the development of 5G technologies.

The problem

The definition of the 5G (planned for deployment in 2020) is in progress. Focusing on 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 5G technologies is anticipated to be considered in both sub-6 GHz and millimetre wave (mm-wave) spectrum bands to support a significantly increased user density to meet its promises. Testing at mm-wave bands presents fresh challenges due to the increased losses, both within the system and in free-space, whereas massive multiple-input-multiple-output (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 parameter will be interference from nearby users. The development of 5G systems is further complicated as a result of the nonlinearities introduced when developing highly efficient microwave systems. Furthermore, despite that test equipment is available for MIMO under the current 4G (fourth-generation) communications technology, activity within the current COST IRACON, the earlier COST IC1004 and COST 2100 illustrates that the measurement issues have not been fully resolved. Hence, metrology to underpin all aspects from signals, devices to systems is essential for 5G communication development, manufacture and deployment. The identified problems to solve are a sound definition of Signal-to-Interference-plus-Noise-Ratio (SINR) and for traceable nonlinear and MIMO measurements both below 6 GHz and at mm-wave frequencies. To meet these needs, both validated test methods and a link to standards bodies are required.

The solution

This project developed three important inter-linked metrological capabilities for 5G mobile communication technologies, namely traceable SINR, MIMO, and nonlinear measurement to cover the signal, component, and system levels. The key project achievements are: 1) robust definitions of SINR applicable to future communication systems; 2) improved metrology for traceable MIMO antenna system using the developed 5G testbeds; 3) traceable metrology for nonlinear 5G components and devices; 4) a valuable EU knowledge-base expertise and resource for those using and requiring state-of-the-art measurements for applications in production, manufacturing, testing, research and development.

Impact

High bandwidth mobile communication is an essential tool for wealth creation by EU citizens, illustrated by a demand-led compound data growth rate of 40% per year. For the first time in the world metrology activities are being carried out in this project before the roll out of the next generation communications. The timing of this project is ideal for collaborating with the 5G standards bodies as the relevant standards have not yet been being finalised. The main impact of this project has directly affect towards the definition of 5G technologies through the inclusion of new methods and means. The impact has been assured by the participation of three EU national measurement institutions (NMIs), along with industrial partners and two largest world-leading 5G research centres (with large industry fan-out). This project has enabled the participated EU NMIs to establish new measurement capabilities to keep pace with emerging 5G technology developments. The enhancements to these capabilities have enabled the project partners to establish and provide traceability in new areas of measurement required by the emerging 5G technologies, and have improved the associated measurement uncertainties to underpin all aspects from the signal, component, and system levels. The developed methods and technologies will enable instrumentation manufacturers to develop innovative solutions to meet the 5G industry's current and future needs.

The EU 5G communication research effort will benefit from dissemination of research results and access to facilities developed under this project. This project's achievements have been disseminated to industry, academia and standards bodies that develop the necessary infrastructure and standards for 5G communications. This facilitate the uptake and use of the knowledge produced by the project partners to support of the EU 5G research and development effort and to enable 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 and will give EU industry a significant competitive advantage over global communications manufacturers. Some example impact highlights are: 1) suitable SINR definitions for a range of possible future communication systems has been defined; 2) the developed mm-wave MIMO testbed has already been used by some 5G key stakeholders and industries through remote access; 3) traceable metrology for nonlinear components and devices has been developed and new measurement services has been established.

2 Need for the project

Despite that test equipment is available for MIMO under the current 4G communications technology, 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 is directly relevant to 5G development activities that are being carried out by the 5G communications industry, and academia, to develop the necessary infrastructure and standards for 5G communications. The project assists on metrology development for 5G and on decision regarding the specification of 5G so to support EU 5G communication industry to the competitive edge. The overall need is to provide timely support for EU industry and academia during the development of 5G technologies. To meet these needs, both validated test methods and a link to standards bodies, such as ETSI (European Telecommunications Standards Institute), are required.

At the Global level: At present, 5G wireless research is taking place in many different regions throughout the world. With strong global momentum multiple worldwide research projects are defining the 5G technology requirements. It is envisaged that 5G Networks will be deployed from 2020 and they will provide fast communication, even in a crowded scenario, together with ubiquitous communication for the Internet of Things (IoT). Focusing on 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. Nevertheless, standardisation work faces the tough challenge of responding to the high public demand for universal, dynamic, user-centric and data-rich wireless applications in relation to the 5G wireless communication system.

At the European level: For the European citizen, mobile communication is an essential part of modern life and as a consequence mobile internet traffic demand is growing at over 40 % per year (see https://ec.europa.eu/digital-single-market/en/news/broadband-big-pipes-potential-growth). This growth rate will require 5G mobile networks deployed from 2020 to provide a data transfer rate in excess of 1000x that of 4G communication systems compared with a 2010 baseline (and x1 million by 2030). In the EU the H2020 program sets a strong position for Information and Communication (ICT) 5G research. The European Commission has already identified a strong link between good communications infrastructure and economic activity and its flagship projects – “METIS” (Mobile and wireless communications Enablers for Twenty-twenty Information Society) and “METIS-II”, within FP7 (the Seventh Framework Programme for Research and Technological Development) and the Horizon 2020 ICT framework aims to provide the definitions for 5G communications, to develop the overall 5G radio access network design, to provide the technical enablers needed for an efficient integration and use of the various 5G technologies and components currently developed. Other EU funded 5G communications research has identified a need to evolve the modulation and coding schemes to overcome constraints due to the user equipment hardware. These projects have already identified a need for further development work on fundamentals (system optimisation/standardisation/trial) during the period 2015-2018. The timing of this research project has been well aligned with this window, providing metrological support for Horizon 2020, EMRP JRP IND51 MORSE, EMRP JRP SIB62 HFCircuit and future COST activities (currently COST IRACON).

At the technological level: Challenging complex performance requirements have been identified for new 5G systems covering latency (1 ms – 1 s), link density up to 106 km^{-2} and throughput up to 1 $Tbits^{-1}km^{-2}$. In addition a range of mobility up to 500 km/hour has been considered with carrier frequency operation over a few hundred megahertz to mm-wave. A raft of new technologies is anticipated to be considered in both sub-6 GHz and mm-wave spectrum bands to support a significantly increased user density to meet its promises. Metrology to underpin all aspects from signals, devices to systems is essential for the development, manufacture and deployment of 5G technologies.

Several technical challenges have been selected as the key areas where the metrology is difficult or in an early stage of development. Testing at mm-wave bands presents challenges over massive-MIMO antenna system characterisation due to their higher losses, interferences and potential hardware imperfection. The high density of users will mean that a critical parameter will be interference from nearby users rather than noise. Also, linearity will be important otherwise stronger nearby signals will swamp the low-level signals from the base-station. Hence the identified critical areas where enabling metrology is needed are: a sound definition and traceable measurement of SINR, traceability for MIMO measurements at mm-wave frequencies, and traceable nonlinear test methods. Also, from the executive summary of Networld2020 whitepapers: Demands on 5G systems are expected to be, “throughput (1000x more in aggregate and 10x more at link level), service-level latency (1 ms for tactile Internet and below 5 ms for 2-8 K change in view, at 30-50 Mb/s), energy efficiency (90 % less consumption for the same service compared to 2010 levels), coverage (global and seamless experience), battery lifetime (10x longer)”. This means that measuring SINR, MIMO over ultra-wide spectrum and energy efficiency will be very important for the design of 5G systems. The following provides the relevant needs in details.

Needs for Definition and traceability of SINR: The performance of current wireless communication systems is reduced by losses in the RF components. Traditionally, system performance has been measured using conducted tests with omnidirectional Gaussian noise. However, a 5G urban environment will be dominated by competing signals, rather than Gaussian noise. This adds several dimensions to the problem of measurement and specification as an interfering signal will now have time and frequency signatures and there will be spatial relationships between the target and interference signals. The supporting metrology will need to traceably measure SINR over a wide frequency range. The measurement of Gaussian noise is well understood but this is a new problem and there will be a need to work with industry (e.g. mobile operator) and standards bodies, such as 3GPP (3rd Generation Partnership Project), to define the language, terminology and definition for SINR.

Needs for Traceability of MIMO measurements: Using available spectrum from a few hundred MHz to mm-wave presents design and measurement challenges for MIMO, reconfigurable and beam-forming antenna systems, the RF electronics and signal processing. Despite that, test-equipment is available for MIMO under the current 4G (LTE) communications technology, activity within the current COST IRACON, the earlier COST IC1004 and COST 2100 illustrates that the measurement issues have not been fully resolved. Furthermore, for 5G communications, the supporting metrology for traceable MIMO antenna system measurement will need to be further extended to accommodate higher areal density of interference signals and operation at mm-wave frequencies. Developing traceable methods and an understanding of the uncertainties for the devices and test environments will support test equipment manufacturers nevertheless testing these performance envelope extremes, which will present significant metrology challenges.

Needs for Metrology for non-linear measurements: Earlier generations of mobile communication (2G, 3G and 4G) focussed on spectral efficiency but in 5G this must also be balanced against cost and energy efficiency. Achieving energy efficiency is a multifaceted problem. Transmission efficiency depends on the hardware and components so nonlinear parameter characterisation play an important role. Currently, nonlinear measurements are made by changing the output load impedance seen by the device under test using a Nonlinear Vector Network Analyser. This approach may no longer be practical for the range of frequencies and ultra-wide bandwidths that are proposed targets for 5G and especially if the sub-system under test will only operate correctly with properly constituted waveforms. New metrology will be required to support these developments.

3 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.

4 Results

Test equipment is available for MIMO under the current 4G communications technology but activity within the current COST IRACON (Inclusive Radio Communications), the earlier COST IC1004 and COST 2100 illustrates that the measurement issues have not been fully resolved. This is the first metrological focus project in the world and has enabled EU NMIs to enhance existing facilities, to develop the required capabilities for 5G antennas, signals, devices and system measurements and to support instrument and wireless system manufacturers. Additionally the results of this research and the knowledge gained has helped EU NMIs and industry to develop solutions to address 5G metrological problems. The project has carried out inter-laboratory studies by involving industry and academia to establish a means of comparison between measurement techniques which will enable the best methods for industry to be identified and exploited. The relevant key achievements of the project with respect to the aforementioned technical objectives are:

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

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

   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. This technical objective focused on definition and development of traceable methods to measure SINR over a wide frequency range – working with industry standardisation bodies such as 3GPP to define the language, terminology and definition of SINR; developing traceable and practical methods of measuring system performance with respect to the parameters defined in the definitions activity.

   As a starting point, and in parallel with studying the existing body of work in this area, a consultation process with industry was carried by NPL, CMI and SURREY 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 (loaned from Keysight) 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 (OTA) test measurements was linked to RF power levels and to data throughput. OTA 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.

Strategy and approaches:

This technical objective has been divided into three parts. In addition, several antennas have been developed for use in the MIMO measurement campaign in the ISM (industrial, scientific, and medical) 2.4 GHz frequency band.

1. *SINR Definition:*
   1.1. Literature review and industry consultation
   1.2. SINR definitions for SISO with two coding schemes
   1.3. SINR definitions for MIMO with at least two sources of interference
2. *Evaluation of SINR definition:*
   2.1. Simulation of two coding schemes for SINR including existing formats (e.g. 4G)
   2.2. Antenna design for test trial
   2.3. Channel sounding experiment at 2.4 GHz using antenna design
3. *Traceability of SINR:*
   3.1. Formulate measurement chain and associated uncertainty budget
   3.2. Traceable measurement based on the aforementioned SINR definitions

The adopted strategy resulted from consultation with industry. A survey of existing work were carried out prior to embarkation on any theoretical or evaluation studies. Once this was completed revised definitions that would be appropriate for 5G were proposed and a modelling/simulation campaign and several measurement campaigns to test these definitions were carried out.

Interaction with standards committees:

3rd Generation Partnership Project

Liaison with the 3rd Generation Partnership Project (3GPP), the primary standards organisation for mobile communication standards, is difficult to achieve as NPL is not able to access this group directly. As a member of the 5GIC (5G innovation centre at the University of Surrey) our results can be reported back to 3GPP through the 5GIC standards sub-group (SSG), at the University of Surrey, who have members who participate in the 3GPP standards activity (RAN4). 3GPP are currently under significant pressure at present to provide early releases of 5G so that the if the key feedback that we have received is that their focus is the early delivery of the 5G standards and interim standard, which should be available. Keysight, a member of the project consortium, has provided some feedback to focus our activity.

ETSI

ETSI has established a millimetre Wave Transmission (mWT) Industry Specification Group (ISG) to provide a platform and opportunity for companies and organizations involved in the microwave and millimetre-wave industry chain to address the challenges involved in using this spectrum. Participation in this pre-standards group is allowed and we have attended two plenary meetings and a number of the telephone meetings.

Industrial consultation meeting:

A SNIR Workshop was organised by SURREY and NPL held on the morning of 9th October 2016 at the University of Surrey. There were 19 attendees present or by telephone link. The aim of the workshop was to consult directly with industry and members of standards bodies to identify clear requirements for a definition of SINR as well as traceable methods to characterize such metrics. The structure of the meeting was an introductory overview of this project with a summary of the key questions was presented and this was followed by a structured discussion. The output from the workshop provided valuable guidance on the focus for the SINR work.

The key response is that the “interference” contribution is significant and its impact may be disproportional compared with AGWN. This is particularly true for narrow-band and “bursty” signals and their effect on legacy systems, particularly in the ISM bands. MIMO and other complex antenna systems offer additional degrees of freedom. Consequentially, the definitions may be more complex and possibly an algorithmic approach will be necessary.

SISO and MIMO SINR definition:

Two additional definitions of SINR for SISO have been formed by CMI, NPL and SURREY in consultation with industry requirements for standardisation as metrology requirements for 5G communications. The existing definitions are applied to in-band SINR. These definition are detailed below:

Definition 1 – SINR for Adjacent Carriers

In the immediate to long-term, it is expected that some existing spectrum will be re-farmed to widen the spectrum availability for wideband 5G devices as well as narrowband Internet of Things devices. 5G devices will be using spectrum alongside legacy 4G systems in adjacent bands. Such a scenario is illustrated in Figure 1, where a 5G waveform is operating in a neighbouring band to a legacy 4G orthogonal frequency division multiplexing (OFDM) waveforms are supplemented by two additional definitions:

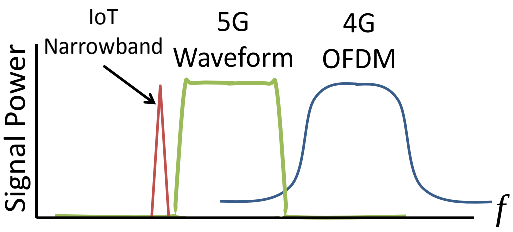


Figure 1 Illustration of SISO SINR definition 1 for adjacent channel interference.

Definition 2 – SINR for mm-wave small cell access links

This definition is aimed at mm-wave to cover to both immediate and long term uses of future generation communication networks. This definition is specifically aimed at SINR in small cell access at mm-Wave (above 24 GHz) where the interference scenarios are not yet understood. A specific test scenario is illustrated in Figure 2, where two neighbouring small cell access points, in close proximity, use highly directional antennas. Direct Tx/Rx is line of sight and interference from another transmitter arises from a specular reflection.

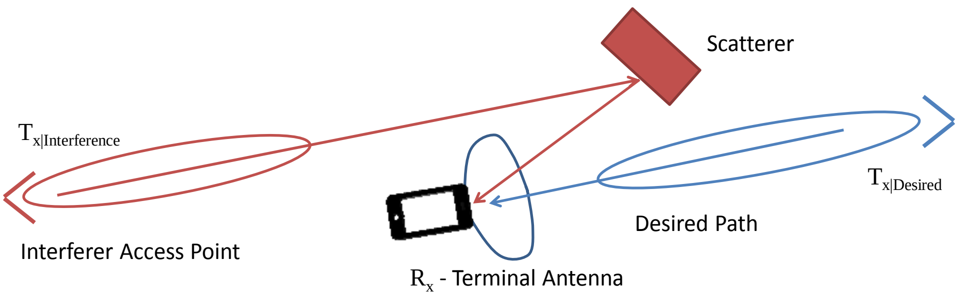


Figure 2 Illustration of SISO SINR definition 2 for mm-Wave small cell access links.

Definition 3 – SINR for Massive MIMO systems

The specification of the chosen definition of massive multiple input multiple output (MIMO) signal to noise ratio as metrology requirements for 5G communications have been formed in consultation with industry requirements for standardisation. Massive MIMO allows the base station to maximise the SINR to the desired user by directing the antenna beam in the desired direction and suppress interferers by directional nulls. This is illustrated in the case of one interferer in Figure 3 where a null in the antenna pattern causes the interferer to be suppressed while the signal in the desired direction is maximised from the main beam.

Having the correct channel state information in order to apply phasing to the array is critical to suppress the interferers. Incorrect channel state information can form a reduction in SINR such as that illustrated in Figure 3 (b) where the desired signal is reduced because the main beam is moved off the direction of the desired signal but also the interferer is now no longer suppressed by a null. Dynamic updating the channel state information is essential to maintain communication above a SINR threshold for all users.

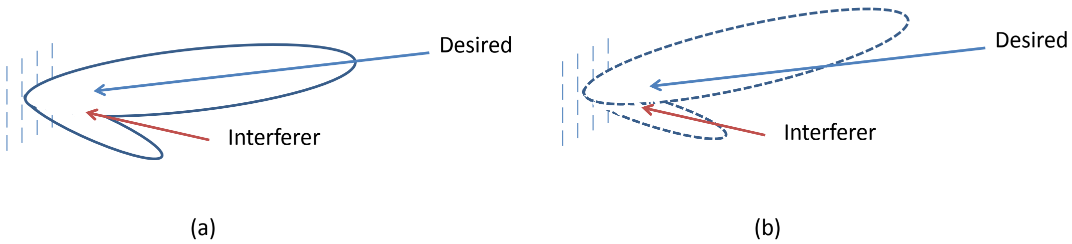


Figure 3 Illustration of the interference scenario for massive MIMO where (a) the SINR is maximised by suppressing the interferer and (b) SINR is reduced due to interference from delayed update of channel state information.

Impact of the radio-communications channel:

In a real environment the received signal may be by direct line-of-sight but the RF signals are reflected and scattered by other objects in the environment such as vehicles, buildings and objects within the buildings themselves, such as a home or office environment. Below 6 GHz these reflections contain both diffuse and specular components. At mm-wave only the specular components will be significant. This affects the SINR for each subcarrier across the channel. The spread of these results does not constitute an uncertainty contribution but the higher SINR of the low channels that will affect the data throughput.

Simulations:

Initially simulations were carried out comprising a 20 MHz, 1200 carrier 64 QAM (Quadrature amplitude modulation) orthogonal division frequency multiplex (OFDM) signal transmitted over a flat-fading channel and a co-channel 64 QAM OFDM interferer. As the frequency channel is considered frequency flat in the evaluations in this section, the choice of bandwidth and number of carriers is arbitrary and will not have an effect on the result. The results were evaluated for fixed SNR values between -5 dB and 20 dB. The relationship between the SINR and EVM is:

$$\mathrm{EVM}\,(\%) = \frac{A}{\sqrt{\mathrm{SINR}}}$$

The value of the gradient, determined by *A* is highly dependent on the QAM order. Some repeated simulations had been undertaken to show how the EVM to SINR relationship changes with different QAM order. The simplest 4QAM is substantially different where SINR cannot be modelled as a single interferer and this will cause a consistent shift in the quadrature phase resulting in a near constant EVM. This observation is noteworthy with regard to cases where additive noise from interference cannot be modelled as white Gaussian noise.

Comparison of SINR and EVM for OFDM and FBMC (Filter Bank Multicarrier) waveforms and co-channel interference at low QAM orders

To verify that the evaluation of SINR based on EVM is waveform independent, 1200 carriers over a 20 MHz bandwidth were used for the evaluation. The same setup was applied for the FBMC waveform and a QAM order of 64. The results were clearly consistent though minor adjustments to the value of “A” in the modelling would be necessary in practise. This is nonetheless no different to calibration procedures that would be necessary in ensuring the prediction model was tuned for conformance testing stage accounting for any radio frequency (RF) impairments in the device. The results showed that at high levels of interference the results rapidly reach a saturation point with BER even with a low order of QAM, suggesting that white Gaussian noise is not a representative model.

Modelling of OFDM pilot + OFDM adjacent channel interference

The simulation was performed using Keysight SystemVue. The base-band signal generation can be described as: Two LTE signals (20 MHz bandwidth, 100 resource blocks each) generated with different mutual center frequency shifts (adjacent channel, in-band interferer or a combination). The amplitude of the interfering signal was varied and the noise density block was added to the composite signal. The frame mode was FDD, 1 Tx antenna, LTE 256 QAM enabled, reference signal power per subcarrier and symbol (energy per resource element, EPRE) was -25 dBm/15 kHz, the spectrum was shaped with a low-pass FIR filter with 195 taps.

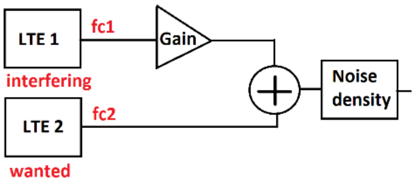


Figure 4 Simulation of the OFDM pilot + OFDM interference.

The EVM measurement has limitations for a blind non-data aided receiver as at high EVM values the closest constellation point may not be the correct decision, decreasing the EVM. The data is sent as blocks allowing correction of multiple errors, the bit-error ratio and block-error ratio provide a degree of data-aided correction to extract the correct EVM.

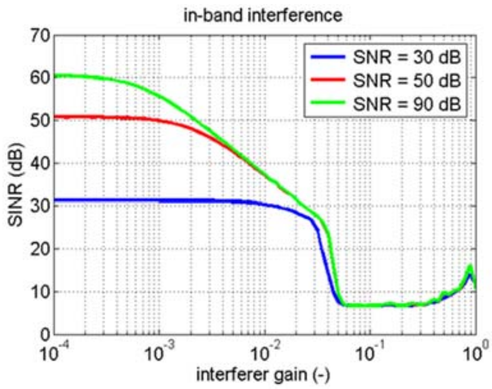


Figure 5 Example simulation results.

SINR Evaluation in Frequency Selective Channels for a Massive MIMO Scenario:

Massive MIMO is a high priority case for 5G standardisation and evaluating SINR. It is no longer possible to obtain full channel-state information (CSI). Instead, pilot signals from the base station give a channel state estimate to apply a zero forcing pre-coder to reach multiple users assumed to have single or multiple antennas. The pilot signals are potentially subject to contamination from neighbouring cells.

Once the pre-coder is applied as shown in **Error! Reference source not found.**, the pre-coder will cause interference to other users as well as communicate to the intended user. Therefore this can be considered inter user interference. At the same time, pre-coders from neighbouring cells will also cause an inter cell interference, which is hoped to be significantly less. The pre-coder will subsequently be out dated as the mobiles move, and hence the second cause of increased interference is the mobility. It is therefore necessary for each mobile in real time to obtain periodic SINR estimations and report back a CQI (Channel Quality Indicator) as illustrated in Figure 6. This will subsequently inform the base station about whether the pre-coder is sufficiently updated. This is a different evaluation necessary than used conventionally in 4G whereby it is required for the mobile users to reliably report an SINR arriving at the mobile as opposed to the overall received channel quality from end to end.

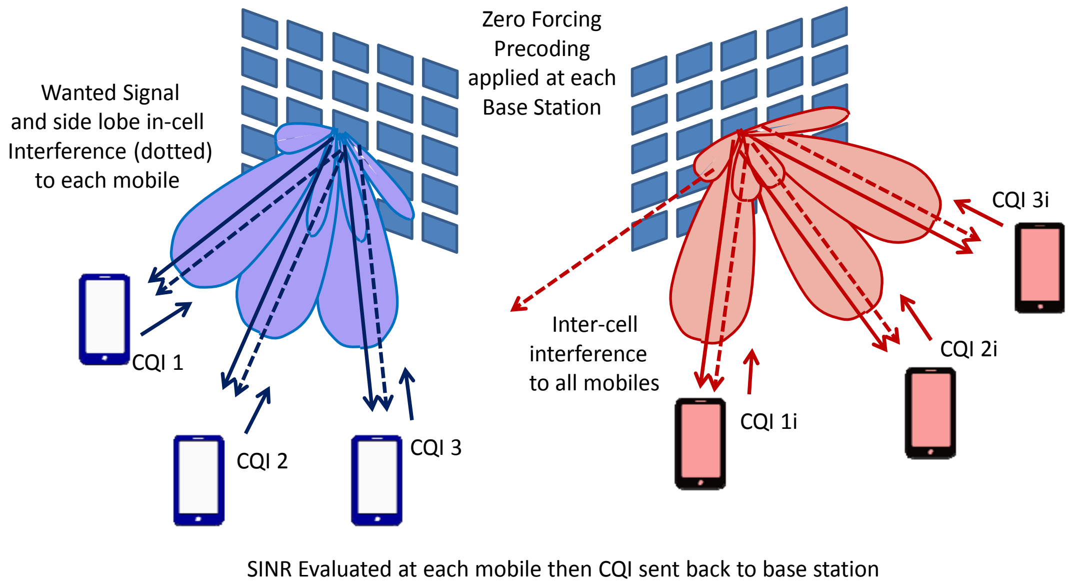


Figure 6 Application of the zero forcing pre-coder with inter user and inter cell interferences.

The propagation channel will experience frequency selectivity and so the evaluations of SINR predicted by EVM using synthetic data may not hold where there is frequency selectivity in the channel.

MIMO Measurement campaign and antenna design:

A measurements campaign was carried out by SURREY at 2.4 GHz using a massive MIMO channel sounder to identify whether frequency selectivity, using closely spaced or widely separated omni-directional receiver antennas, can impact the prediction of SINR. This will have substantial impact on the achievable SINR when using the zero forcing precoding. A specific antenna was designed and prototyped in order to evaluate the angular effects.

Angular Antenna Design:

Several new dual-polarization antennas were designed to facilitate SINR measurements in the 2.4 GHz ISM band resulting from angular rather than spatial separation of receivers. A novel geometrical configuration has been employed to enable several antenna elements to be positioned on common ground plane (see examples in Figure 7). It is also possible to control the gain of each antenna element. The technique has been applied to 4-element and 6-element MIMO antennas, providing polarization diversity gain. When all ports are excited it forms semi-omnidirectional pattern which could be used for transmission and sensing/searching proposes. The limited available space in a shared ground plane, encourages the exploitation of the following three techniques to maximise the diversity performance:

- Additional features have been included to minimize the coupling between adjacent IFA elements.
- Pattern diversity is used to preserve a low envelope correlation between the elements.
- The relative angle between IFA elements was chosen as 2π/n, where n is the number of elements.

The 4-element and 6-element MIMO antennas were fabricated and show a measured port-to-port isolation is better than -20 dB.

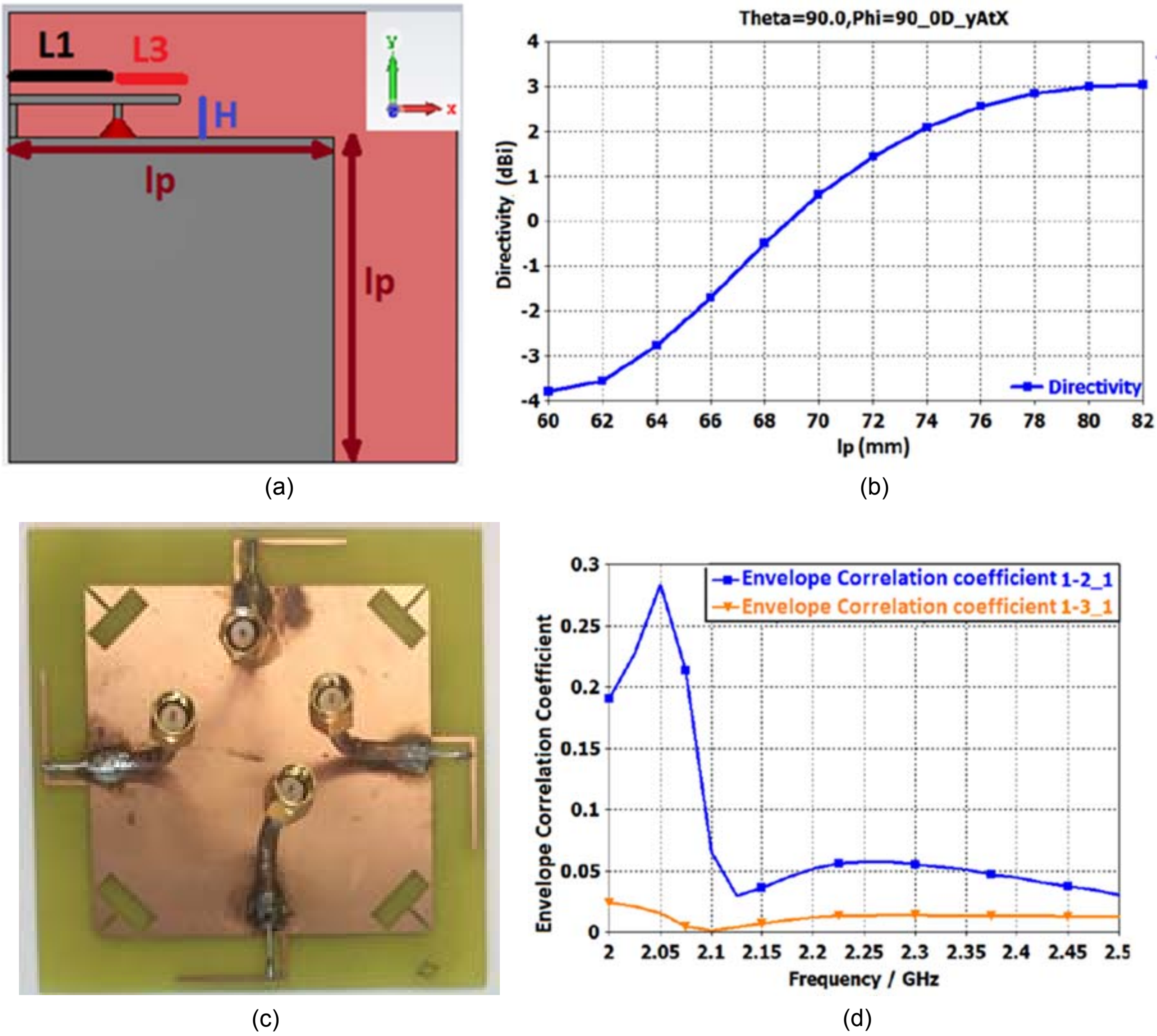


Figure 7 The geometry of the single and four-element MIMO antennas with the envelope correlation coefficient: (a) Single element dual polarization antenna; (b) Directivity of single element antenna; (c) Four-element antenna; (d) All possible combination of envelope correlation coefficient for the 4-elements MIMO antenna.

Measurement Campaign Setup:

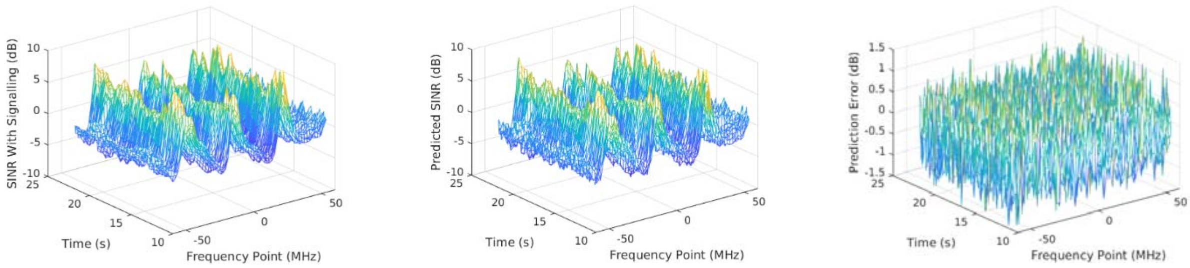
A 32 x 6 MIMO wideband channel sounder setup was used to undertake the measurements over a 200 MHz bandwidth (of which 120 MHz was used for evaluation) at 2.4 GHz. Therefore it was possible to conduct two 32 x 3 massive MIMO measurements simultaneously as it is required to have greater than ten times the number of elements at the transmitter than the number of single antenna receivers to meet the criteria. The measurement was carried out in an outdoor obstructed line of sight environment with significant vegetation to enable some channel fading but varying separation of beam space between the three receivers as illustrated in Figure 8.

(a) (b) (c)

Figure 8 (a) Plan of the outdoor Massive MIMO measurement area and photographs of the measurement environment showing the 32 element transmit array – (b) for Rx1 to Rx4 at a fixed position and (c) for moving Rx 6.

Measurement Results:

In post processing, a zero forcing pre-coder was applied to the base station elements such that each of the three receivers would have a corresponding pre-coded channel, but interference would be caused by the pre-coded channels of the other two receivers. As depicted in Figure 9, the results show good agreement between the measured and predicted channels for both stationary and moving receivers.



(a) (b) (c)

Figure 9 Measured and predicted results for stationary channel sounder MIMO measurements: (a) Measured SINR; (b) Predicted SINR; (c) Difference between (a) and (b).

Summary of Measurements:

Results of a massive MIMO measurement campaign were evaluated to indicate the capability of EVM to predict SINR where the sources of interference and their magnitude are unknown. The prediction of SINR can be used for a more accurate and reliable CQI, dependent on low prediction error on the SINR with signalling. Such prediction error in a real channel was found not to exceed ±2 dB.

Traceability of SINR and related parameters:

This covers the direct provision of traceability for RF power measured with a range of instrumentation types and industrially important equipment using both directly connected and OTA systems. In-band and adjacent channel interference and CQI have been investigated.

RF power:

The RF power received by the test device is critical as the data throughput collapses from 100% to 0% in a power range of only a few decibels. Since RF power/sensitivity is intimately connected with range and base station coverage this is an important parameter where we need to also know the confidence interval.

In the future, particularly at mm-Wave direct connection will not be feasible because of the fragility and number of the connectors that would be required. Some of the components used in this work would not be required for an OTA measurement. OTA measurements in LTE have been a topic if intense study by EU COST programmes and within industry standards committees.

Proposed systems for traceable SINR measurement:

The objective is to measure and calculate the SINR in a way that is traceable, and therefore system independent. The dynamic range difference between the downlink and uplink excludes broadband RF power sensors and possibly digital oscilloscopes. Frequency-selective instrumentation such as Vector Signal Analyzers (VSA) will have fewer dynamic-range issues.

Digital Real Time Oscilloscope (DRTO) reference instruments are limited by the instrument sensitivity, typically 5 mV/div and so the typical peak signal level is -20 dBm or higher. These instruments also create RF spurs that can fall within the measurement bandwidth. If a VSA is used in place of the DRTO then the peak signal level can be lower (-50 dBm). This should be compared with the typical test level for a UE (-70 dBm) or the limiting value that is used for pass-fail testing (about -90 dBm).

Oscilloscope-based measurements:

The signal, interference and noise was fully mathematically modelled in Keysight SystemVue software and then uploaded to the RF generator instead of generating those separately using different generators. A high-end oscilloscope was used to capture the signal trace at the RF frequency. The signal is mathematically down-converted and filtered to recover the modulation waveform (see Figure 10).

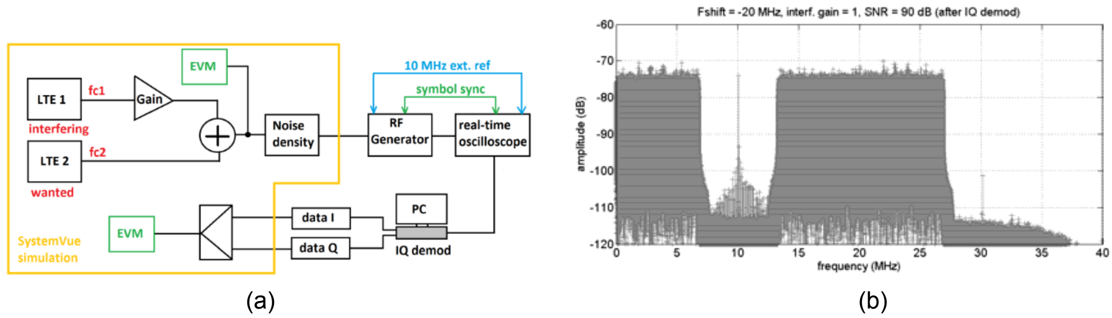


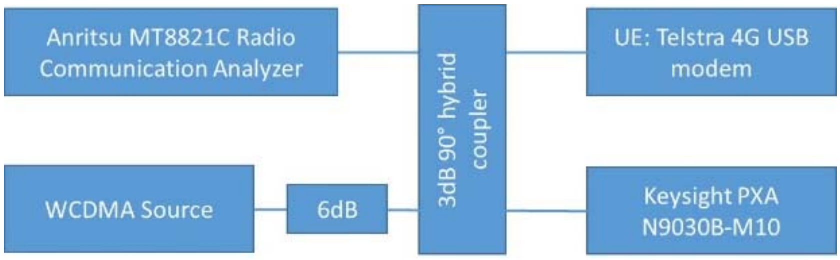
Figure 10 Measurement system and experimental results for RTDO measurement: (a) Measurement system; (b) Digital spurs removed during IQ demodulation

The Oscilloscope traces were measured over a 40 ms time epoch, corresponding to approximately 30 frames (50 million samples) at 1.25 GS/s in a bandwidth of 2.5 GHz (undersampled). These results were IQ demodulated, filtered, down-sampled to 92.16 MS/s and the I, Q components were saved into text files. The EVM of the stored results was calculated using the SystemVue LTE_EVM block and the EVM resulting from the oscilloscope traces was compared with the simulated result.

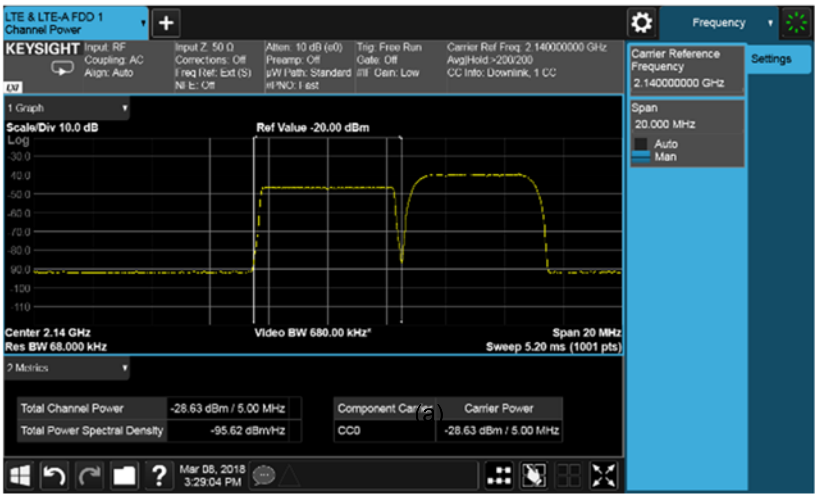
SINR measurements using phone-tester and EVM measurements:

The Radio Communication Analyser is a measurement instrument platform that is able to perform both transmitter/receiver characteristics measurement of radio terminals in mobile communication systems and call processing test with one unit. It supports LTE-advanced and LTE communication standards and has the capability of measuring two UEs with a MIMO downlink. The UE, operating in Bands 1, 3 and 7, was a Telstra 4G USB modem and Agilent SIM, allowing the data to be looped back to the Radio Communication Analyser.

A 3 dB 90° hybrid coupler was added to allow uplink power monitoring and injection of noise and interference signals. A Keysight PXA model N9030B-M10 loaned from Keysight DK was used to monitor the EVM of the signal to the UE. The test measurements compare the CQI reported for the downlink to the UE together with the measured EVM. Additional interference (WCDMA) and noise signals were provided by a separate signal generator. The measured results are shown in Figure *11*. The low EVM at high interference values shows that the wrong constellation point is being applied.



(a)



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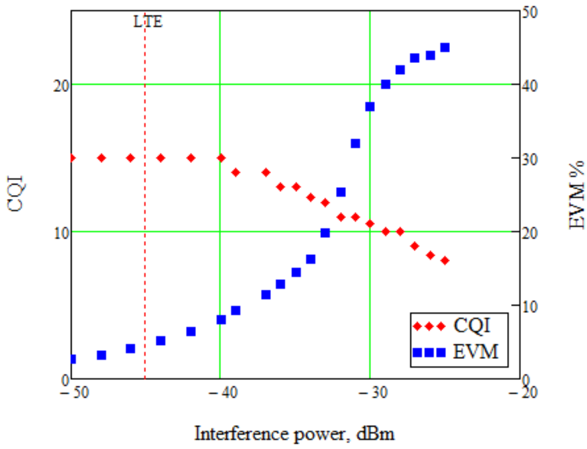


(c)

Figure 11 Measured results for an adjacent-channel interference signal: (a) Measurement system; (b) Screen view from PXA; (c) EVM and CQI calculated for adjacent channel WCDMA interferer.

SINR OTA in a MIMO environment below 6 GHz:

Spatial and polarisation diversity MIMO and massive MIMO are Key features of 5G to maximise the available throughput to a single or multiple users. Measurements were made in two different environments: a fully anechoic chamber (operates at frequencies above 400 MHz) and the partially reflecting screened control room with metallic walls. The chamber is temperature controlled at (22 ± 2)°C. The system tested comprised a Keysight E6621A PXT wireless communications test set and NETGEAR MR1100 Mobile

Router (UE). The uplink and downlink signal power were monitored using a calibrate VSA (10 MHz bandwidth) and the RF power calibration difference between the two instruments was 3.8 dB.

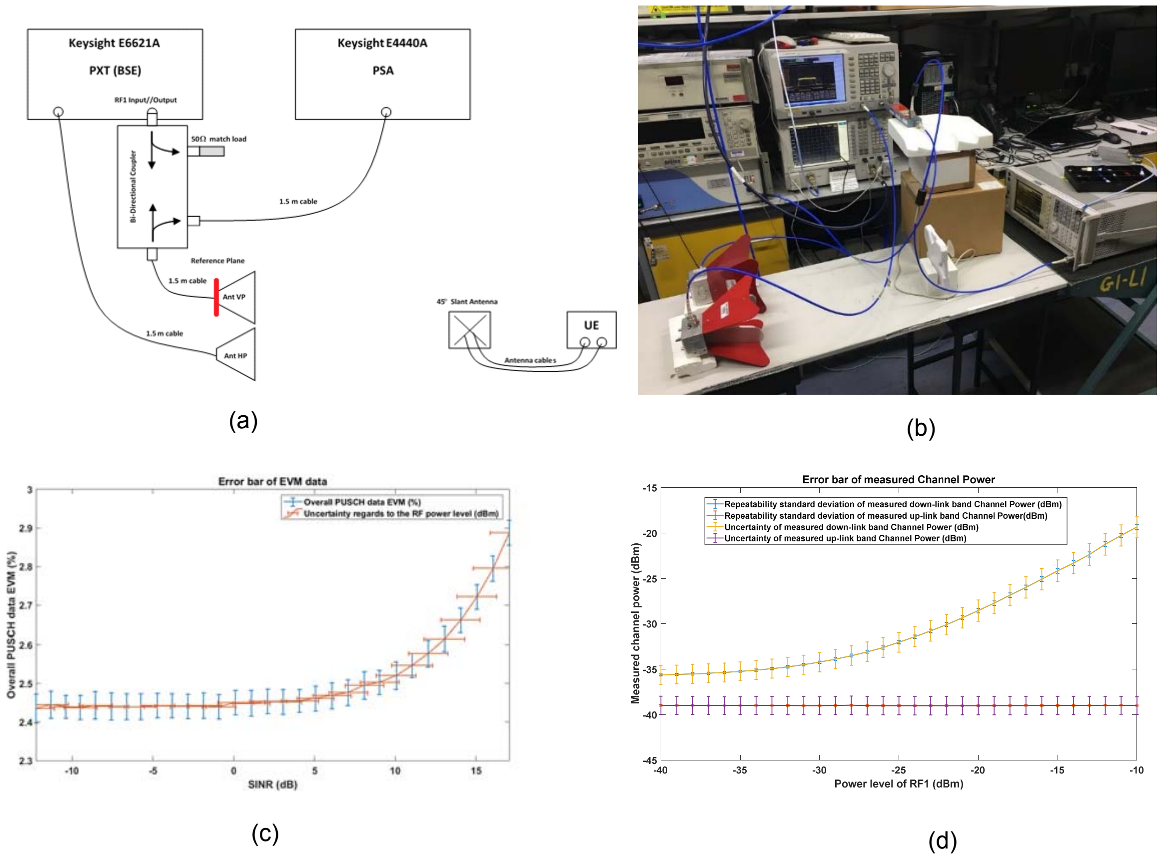


Figure 12 Measured results for the uplink in the control-room: (a) Measurement system; (b) Measurement system in the control room; (c) UL EVM measurement results with 200 repeats in control room with metallic walls for a DL interferer of -40 dBm. The instrument EVM contribution is about 2.43%; (d) DL and UL Channel power measurement results with 200 repeats and DL AWGN interference signal at -40 dBm on both RF ports in control room with metallic walls.

The MIMO results show significant statistical variation (see Figure 12). Measures, such as throughput will exhibit non-Gaussian statistics. Despite this issue, a key point is that the block data recovery process provides a degree of separation for the individual MIMO channels, provided this information can be accessed.

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

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

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, by NPL, Chalmers and SURREY, respectively. Also, Keysight DK has provided support on the system design and validation of Chalmers' software simulator. 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.

Strategy and approaches:

This technical objective has been divided into three different parts:

1. *Testbed development for MIMO measurements at mm-wave frequencies:*
   - 1.1. NPL 2 x 2 mm-wave MIMO testbed
   - 1.2. Chalmers 8 x 2 mm-wave MIMO testbed
2. *Evaluation of the testbed and interference measurement campaign at mm-wave frequencies:*
   - 2.1. Internal interference
   - 2.2. External interference
3. *Evaluation of SINR measurement campaign both at Sub-6GHz and mm-wave frequencies:*
   - 3.1. SURREY 32 x 3 sub-6GHz MIMO testbed
   - 3.2. Validate the defined SINR definitions

Develop mm-wave 5G MIMO testbeds, including multiple antenna base station and terminal receivers:

Two mm-wave MIMO testbeds were constructed, both will be shortly discussed here, we start with the NPL testbed, which was used as precursor to improve the design of the mm-wave testbed MATE, which will be subsequently discussed.

NPL Testbed:

The NPL testbed is a 2x2 mm-wave MIMO testbed and it is capable of performing spatial diversity MIMO transmission. It was built to gain experience that could be fed into the design of future mm-wave massive MIMO testbeds. The MIMO decoder uses the measured data at the receivers, and previously obtained channel state information in the form of a measured H-matrix, to recover two simultaneously transmitted frames.

The NPL testbed was built using two vector signal transceiver (VST) system modules with a real-time signal processing software defined radio (SDR) capability, two pairs of standard gain horns at the transmit and receive ends and frequency up and down conversion hardware. The VST modules are acting as baseband part of the MIMO system and have a frequency coverage from 65 MHz to 6 GHz. Providing a suitable filter is chosen to limit spurious output, the system is envisaged capable of operating with RF frequency range from 20.65 GHz up to 46 GHz. Figure 13 presents an illustrative diagram of over-the-air (OTA) test setup for the NPL mm-wave testbed.

The up-conversion and down-conversion hardware uses a frequency distribution unit, a DC feedback circuit is used to stabilize the LO amplitude of the frequency distribution unit. A filter is used to suppress the image frequency of 20 GHz. For a two-channel system, the transmit-end uses a power splitter to allow the LO to drive both mixers. The same technique is employed to share the same LO drive between the mixers at the receive end.

An initial study was performed to select amongst the possible options for the mixers and up-conversion and down-conversion systems. The chosen system configuration uses the NI VST system to generate the MIMO system coupled to broadband mixers. For compatibility with the MATE system, operating at 28.5 GHz, an intermediate frequency (IF) frequency of up to 6 GHz can be used, yielding a minimum LO frequency choice of 22.5 GHz.

Each component was characterized individually to decide appropriate RF power level settings and to verify performance. After initial testing the design was revised to further suppress distortion and unwanted RF components. This was done by choosing different LO frequencies for the RX and TX to avoid the degenerated case, where distortion product fall on top each other and cannot be individually investigated. Furthermore, bandpass filters may be inserted, when needed, to improve EVM by removing unwanted RF components. Measurements have shown EVM below 1% are possible without the need for digital pre-distortion. At the same time an appropriate filter will reduce LO breakthrough which was experimentally verified. The residual components and nonlinearities have been measured for the system including the new filter using an RF power sweep of a two-tone signal. The results show that the improved filtering removes the residual LO breakthrough term and the third order intercept power is 10.5 dBm and this nonlinearity is mainly attributable to the amplifier.

The NPL system was tested both inside as well as outside anechoic chambers. Differences were noted due to multi-path effects in a normal environment. Coupling between the antennas were studied in either a co-polarized or cross-polarized configuration. The coupling between of the directional standard gain horn antennas are insignificant in both configurations. Note however that the overall coupling for the co-polar configuration is slightly higher then cross-configuration. Also, the matching performance of the antennas has been observed. It is envisaged that this would introduce a difference in the link performance between the two channels in the MIMO system, which was subsequently shown at the real world co-located tests at Chalmers.

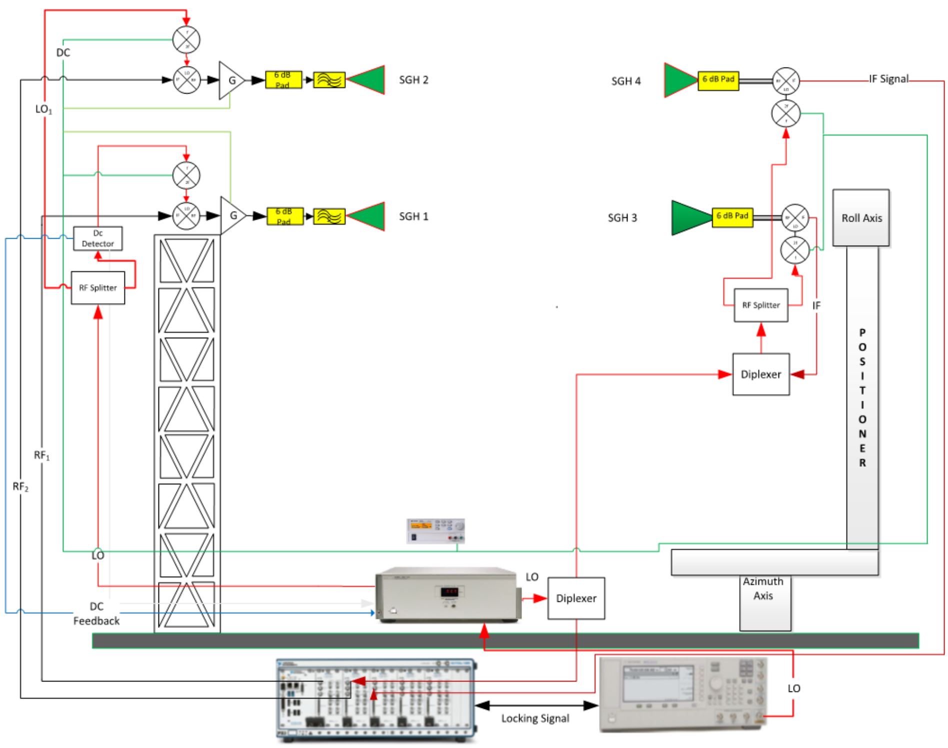


Figure 13 Illustrative diagram of OTA test setup for the NPL mm-wave testbed. Note that the two diplexers are not installed into the system unless the testbed is mounted on a positioner.

Chalmers MIMO testbed – MATE:

Multi-antenna testbeds allow the study of limitations of future communications system on realistic hardware. Before going into the use of the testbeds, here we introduce a typical configuration of the mm-wave Massive MIMO testbed (MATE) testbed at Chalmers with its associated server-client infrastructure. Several requirements that were imposed on the design are summarized below:

- Enables various kinds of mm-wave research.

- Large bandwidth.
- Off-the-shelf components.
- Independent transmitter and receiver.
- Easy to access by users.
- Possible to extend to real-time.
- Scalable for future requirements.

These requirements translated into a testbed that operates between 28 – 31 GHz, with 1 GHz analog bandwidth per transmitter or receiver. MATE supports up to 18 channels, which can be used in various configurations, with up to 16 transmitters and up to 9 receivers. Field-programmable gate arrays (FPGAs) are available at each individual transmitter or receiver. The RF frontend is fully independent of the baseband hardware and software, thus can be replaced by other RF hardware, enabling different frequency bands. MATE is easily accessible to users by a remote access interface, for which a MATLAB client has been created, which takes care of all communication aspects, enabling worldwide access. This client can be called as a function in MATLAB, thus allowing ease of integration in exiting software processing code. The mm-wave testbed can be divided into three parts, baseband hardware, software and RF frontend hardware. The full system is shown in Figure 14.

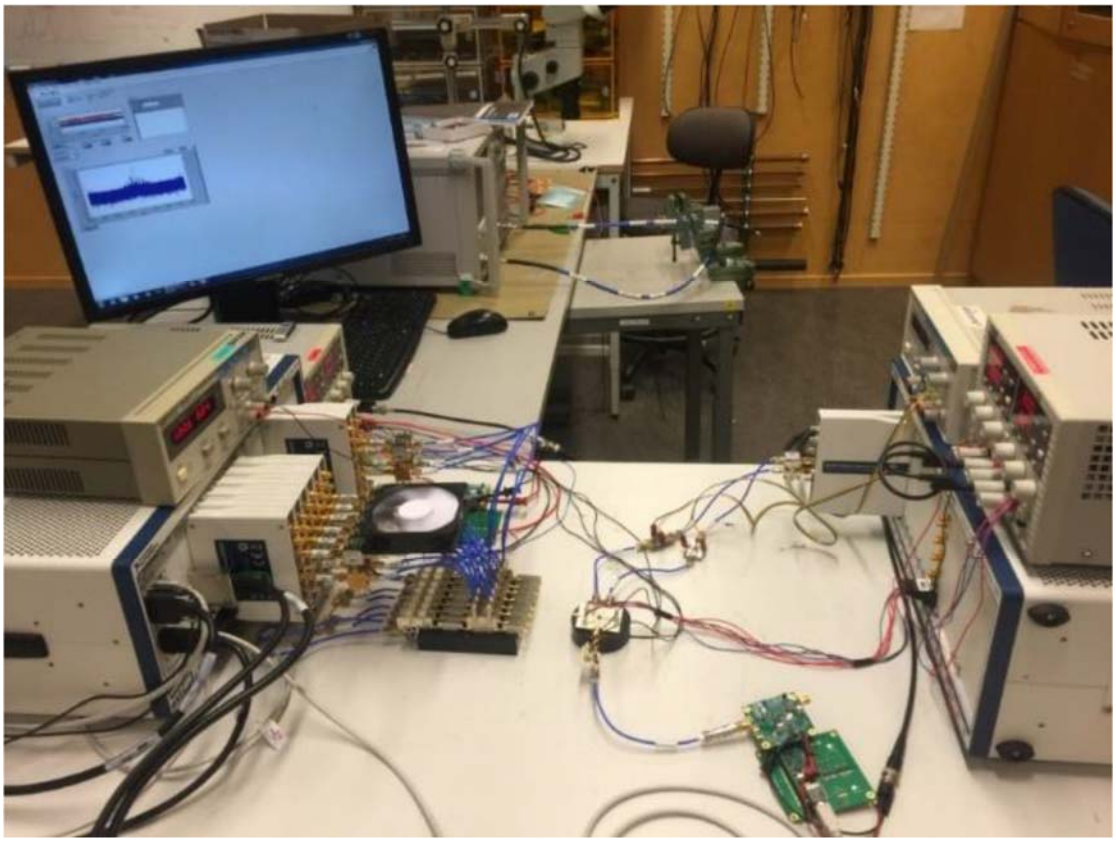


Figure 14 Photographs of a typical configuration. Note that TXs on the left, RXs on the right.

Baseband Hardware:

The MATE baseband transmitter and receiver hardware consists of analog-to-digital converters (ADCs), digital-to-analog converters (DACs), FPGAs, sample clocks and triggering. The baseband of the multi-antenna transmitter has its own sample clock, triggering and reference oscillator which is realized fully independent of the receiver, which has its own sample clock, triggering and reference oscillator. To ensure the baseband signals are coherent, one sample clock is distributed to all DACs and another to all ADCs. Trigger signals are latched to the sampling clocks to enable coherent transmission or reception.

Software:

The software takes care of synchronization, sample clocks, data transport between (host) memory and FGPA, as well as client-server communications. The software consists of several parts: code running on the FPGAs, code running on the host controller. Additionally, the server running on the controller, as well as the webserver at a hosting provider and finally the client running at the user's computer. The server is implemented in MATLAB and is similar to the server constructed for Chalmers' online RF WebLab (www.dpdcompetion.com/rfweblab) system. The MATE software clients take care of the communication between the user at their workstation and the MATE testbed. This is performed such that the user can use the client as a MATLAB function, and simply include it in his/her own code.

RF frontend hardware:

The mm-wave RF hardware is constructed from off-the-shelf components, supports >1 GHz analog bandwidth and operates between 28 – 31 GHz. To enable digital beamforming and MIMO signal processing, each TX chain of the system has to be coherent with respect to the other TX chains. To reach this goal we distribute a ~3.5 GHz local oscillator (LO) signal to each of the TX chains, where the LO is subsequently multiplied by a factor of 8. Note that if there is more than one RX, we employ a similar LO distribution for the RX as well. Unwanted products arising from the LO multipliers are suppressed with bandpass filters, after which the LO signals drive IQ modulators, where the baseband I and Q signals are provided by 1.25 GS/s DACs. After the IQ modulator a second identical bandpass filter is applied. The signal here is connected to an antenna. The RX chain is similar to the TX chains. The downconverter IC contains a low noise amplifier and gives out the down-converted I and Q, which are subsequently amplified, filtered and digitized by 1.5 GS/s ADCs.

The construction of the hardware for MATE was completed and the system was made operational in December 2016. By June 2018 over 43,000 measurements have been performed by key stakeholders. Some key features of the testbed are summarized in Table I. When comparing the MATE testbed with existing testbeds in academia, testbeds realized in the low GHz frequency region have much lower analog bandwidth, but more channels. We have realized a large analog bandwidth as well as a high channel count for mm-wave testbeds.

KEY FEATURE OF THE MATE TESTBED

	MATE
Operating frequency	28 – 31 GHz
Analog Bandwidth per TX/RX chain	1 GHz
No. TX	8 (extendable to 16)
No. RX	1 or 2 (extendable to 9)
No. FPGAs	18
RF Output power per TX chain	Max. -4 dBm
Noise figure RX	3 dB[a]

[a] *From datasheet*

Each component was tested individually, as well as the whole system performance. Further the use of directional couplers allows to introduce calibrated reference planes, where initially conventional RF calibration were applied. MATE was calibrated using conventional standards, a power meter, and a spectrum analyser. The NPL testbed was calibrated using a calibrated spectrum analyser. Wideband calibration is discussed in the section on traceability.

We have demonstrated that the MATE testbed at Chalmers is very suitable as a tool within this project, as well as for future mm-wave 5G communication research. Detailed experiments have shown that the testbed is a stable and capable tool for making experiments, and the remote access interface makes studies extremely convenient. Having two complimentary calibrated testbeds available in this project gives unique possibilities to verify, validate, as well as co-locate the testbeds to perform joint experiments, in particular aimed at interference studies.

Extend current traceable MIMO measurement metrologies to accommodate higher areal density of interference signals and operation at mm-wave frequencies:

As shown, two calibrated mm-wave MIMO testbeds were available in this project, which are used to study real communication signals in a realistic 5G mm-wave MIMO interference scenarios. The software used to control the NPL testbed generates the transmitted data using SystemVUE, writes this waveform to the NI VST, transmits and receives a single frame, sends the received data back to SystemVUE to decode, analyse and displays results. The following quality metric we have considered in this work.

Error Vector Magnitude:

Error vector magnitude (EVM) is a measure of the error between the measured constellation points from the decoder and an ideal reference constellation.

Bit Error Rate:

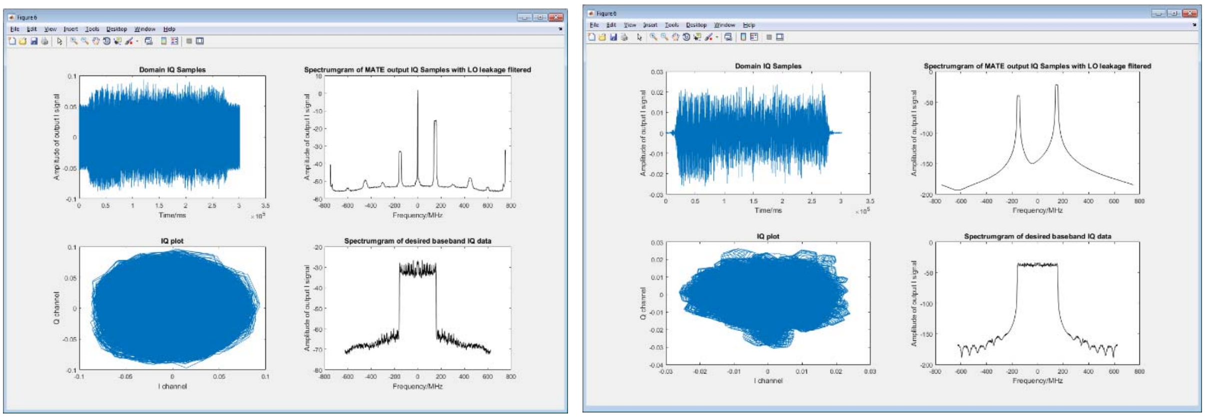
Bit error rate represents the percentage of bits that differ between the data stream that is transmitted and the data that is decode from the received frame.

Estimated Throughput:

Estimated throughput is the number of valid bits decoded from each frame multiplied by the number of frames that could be theoretically transmitted in one second. If the data streams are different the total throughput is the sum of the throughput per channel. Otherwise the maximum throughput is the larger of the two values to account for transmission diversity.

Channel Power:

The channel power is calculated from the captured IQ data for the frame. The channel measurement bandwidth is the same as the expected occupied bandwidth for the frame. The channel power is used to determine signal to noise ratio (SNR) and signal-to-interference-plus-noise ratio (SINR).



(a) (b)

Figure 15 The Chalmers MATE testbed output IQ data (a) with and (b) without using a bandpass filter.

Figure 15 gives a comparison of the MATE test bed output IQ data with and without using a bandpass filter. By integrating Chalmers MATE and NPL 5G test bed code identical code can be used on both systems. Thus, all communication experiments can be executed remotely on MATE as well. This is needed to conduct a comparison between both systems. As well as the subsequent measurement campaigns on internal and external interference. Experiments with external and internal interference were performed using MATE and compared. For an external interferer in a multi-antenna system, the link quality will suffer.

In the testbed, this case is created by using one of the antennas as an interferer, and the rest of the antennas operates as usual and beam forms the communication signal towards the intended user. Then, by varying transmit powers more or less severe levels of interference can be created. The interfering signal is assumed unsynchronized to the intended signal.

Experiments have shown that the distortion is quite Gaussian in its nature. For low interference the measured results are dominated by the additive thermal noise from the receiver low noise amplifier (LNA), and for stronger interference the interference dominates. As can be expected, the SINR increases when we reduce the power of the interference, but we hit a roof when the thermal noise starts to dominate limiting the SINR range of the system.

Interference:

A multiuser MIMO system, as will be the basis in 5G, communicates to multiple users at the same time and at the same frequencies, differentiating between users only through spatial separation. If the channel-state information (CSI) is perfect, the users can be perfectly separated and no interference will occur. However, due to imperfect CSI acquisition, the users will interfere.

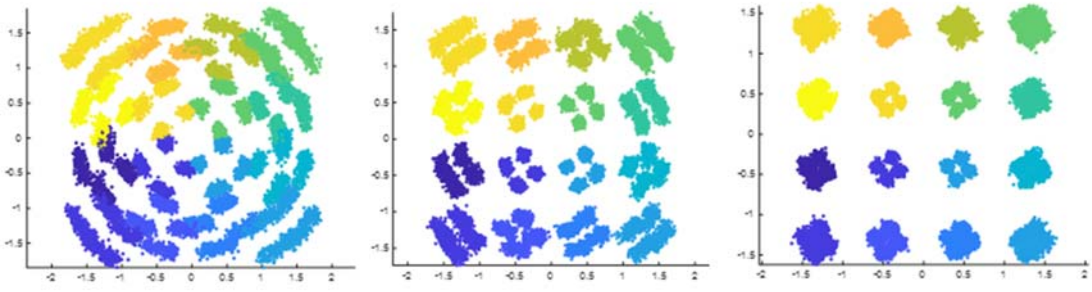
In this experiment the testbed communicates to two users simultaneously and the quality of the CSI was varied to give various amounts of interference power. In the signal design, this corresponds to creating a precoding matrix with the intention to communicate with two users with known channel information. One user acts as a reference user, and the other then becomes an interference source. Now the distortion created is quite non-Gaussian. This is typical for the in-system inter-user interference cases since the users are synchronized within the system. Typically, a given SINR leads to a certain symbol error probability. However, since the in-system interference, with interference that is synced with the useful communication, has such a different probability density function (PDF), it could be expected that even for the same SINR the symbol errors could differ between the external and in-system cases.

As shown, the case with external interference behaves exactly as AWGN (Additive white Gaussian noise); the interference is quite Gaussian. However, the in-system interferer has a much less effect for small interference powers, and then a higher effect when the interference power is large (small SINR), leading to a steeper transition region. The effect is easily explained because of the non-Gaussian nature of the noise. For small values of the interference power, there will never be any symbol errors, since the received signal stays in the correct region always. Then, when the in-system interference is high, a lot of the symbols starts to be wrongly received. The conclusion from these experiments are that the SINR is a quite good quality measure that predicts how good the performance of the system can be.

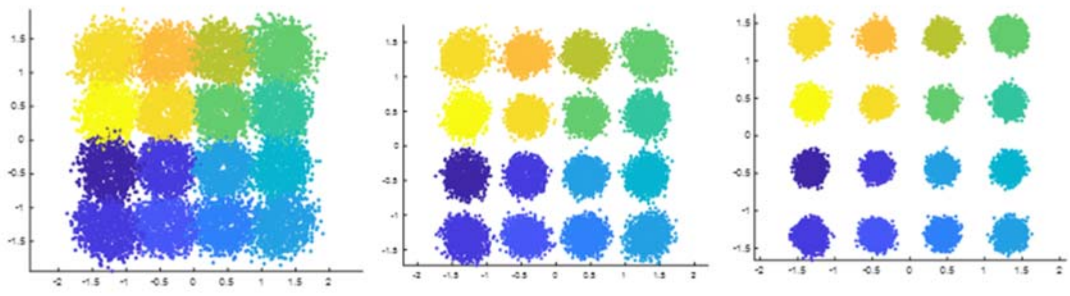
Measurements over the NPL testbed with internal interference were conducted at the fully anechoic chamber at NPL as well as when the NPL testbed was set up in Chalmers. SISO measurement were also made to assess the performance of the test bed in both modes of operation. Some differences in performance of the NPL testbed in a near free-space (i.e. anechoic chamber) and multipath environment were seen. Measurements made with both 5G testbeds co-located, after the NPL system was moved to Chalmers. A series of measurements were made to assess SINR, with one system acting as the desired signal and the other acting as an interference source. Both systems were setup to operate at a center frequency of 28.5 GHz.

Once the two systems were aligned a system level assessment was performed on MATE with no external interference present from the NPL system. Then measurements were performed on MATE with external interference present from the NPL system. The channel power, SINR, EVM and BER were measured using the MATE receiver with NPL interference power level varied.

These experiments demonstrate operational mm-wave MIMO testbeds, co-located to study internal and external interference. An interference study using MATE demonstrated that external interference acts similar to AWGN, whereas internal interference is coherent with the intended signal, which has different consequences for the obtainable BER or SER. Co-located experiments clearly demonstrated the operational aspects of external interference originating from two un-coordinated MIMO systems. Which will be compared in the following section to the theory related to traceable SINR methods.



(a)



(b)

Figure 16 Constellations with three different SINR levels, 13 (Left), 16.5 (Middle) and 13 dB (Right) respectively, for interference originating: (a) internally; (b) externally.

<u>Develop and validate new MIMO measurement approaches and definitions to address the lack of recognised standards for traceable calibration of the spatial field in a complex electromagnetic environment:</u>

Three multiple-input-multiple-output (MIMO) testbeds (2 × 2 mm-wave MIMO, 8 × 2 mm-wave MIMO, and 32 × 3 sub-6GHz massive MIMO) have been used. The aim is to compare and analyses the SINR measured results between the measurement campaigns for: 1) in-band; and 2) out-of-band scenarios. This will help ascertain the strengths and weaknesses of each definition. Note that all these experiments are executed over-the-air in realistic 5G scenarios. Thus, a 5G waveform candidate is employed. Based on the measurement findings, the SINR definition is validated.

To look at the impact of the frequency selectivity of wideband channels, the sub-6GHz massive MIMO testbed at SURREY with the associated measurement setup using MIMO antennas was used. The antenna was designed to analyse the impact of angular separation of antenna patterns against spatial separation on interference, using commercially available omnidirectional antennas.

<u>Sub-6 GHz massive MIMO testbed:</u>

Using SURREY's wideband MIMO channel sounder, it was possible to conduct two 32 x 3 massive MIMO measurements simultaneously. The measurement was carried out in an outdoor obstructed line of sight environment with significant vegetation to enable some channel fading but varying separation of beam space between the three receivers.

The transmit array consisted of 32 dual polar patch elements, while the receiver antennas were commercial omnidirectional monopole antennas with a small ground plane attached to them. It was demonstrated that close proximity, stationarity and fixed position would create substantial interference thus limiting SINR. Wide separation will allow some beam separation to improve SINR between the two antennas.

For angular measurements using the angular antenna, were connected to a six-element inverted-F antenna, which was moved horizontally in the measurement. Therefore, two sets of 32 x 3 angular measurements could be undertaken to evaluate how angular separation affected SINR. There are three different scenarios of SINR that were analysed in this study from three different receivers:

1) In this situation the receiver was stationary but in close spatial separation to two other receivers which would cause substantial interference from the downlinks to those receivers formed by zero forcing. Therefore, this would make a substantially low SINR that is largely static, only changing due to moving scatterers.
2) This receiver was moving, while the two other receivers causing interference from the transmitted modes to those receivers using zero forcing would be highly time variant and also frequency selectivity at each time interval would change.
3) This receiver was connected to the angular antenna and the interference was substantially impacted by having the other two receivers close to it but also there was significant time variant effects as the angular effects changed in each time slot.

Clear different impact on interference was demonstrated in these different scenarios. The ultimate purpose of the measurements was to ascertain what impact frequency selective wideband channels would have over the prediction error when estimating SINR. The results in this project have verified that the EVM has the ability to predict SINR if the waveform has a transmission bandwidth is within the coherence bandwidth of the channel's SINR.

MATE Simulator:

A comparison of the mm-wave Massive MIMO testbed (MATE) hardware at Chalmers and its simulator, entitled 'MATE simulator' and several investigations over the system parameters are performed. The MATE client software allows a user to upload IQ data to MATE for transmission. The client supports transmission using a number of configuration modes. One of these modes is a simulator which uses a software model to simulate the performance of the MATE hardware. Testing was performed on MATE and the MATE simulator using a Cyclic-Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM) waveform, the same waveform chosen for 5G new radio (NR). It should be noted that the MATE testbed is a dynamic testing environment. Antennas are moved around, hardware is changing, and temperature is variable. The MATE simulator, at the other hand, is more static. Thus, there is a need to calibrate the simulator to MATE at a certain point in time; at some other time, there will be discrepancies.

The data transmission between the MATE hardware transmitting and receiving ends would be affected by their allocation hence the associated propagation channel response. i.e. changes in position of MATE antennas and surrounding objects will change the propagation channel response. There is a visible difference between the performance of MATE and the MATE simulator when incorrect propagation channel response is employed in the MATE simulator. Once the correct propagation channel response was employed into the simulator the improvement in the agreement between the MATE hardware and MATE simulator. For investigating EVM and BER performance against SINR, two different CP-OFDM waveforms were generated to represent a desired signal and an interference source. The desired signal power was fixed for all measurements and the interference power level was adjusted in steps to produce varying SINR. The received channel power for the desired and interference signals were measured separately and then the EVM and BER were measured with both signals transmitting at the same time. Also for these test good agreement was found between MATE and the MATE simulator, enabling accurate pre-studies, minimizing the required experiments.

EVM, SINR verification measurements using MATE:

To verify the SINR definition, a comparison of EVM was made for the data frames transmitted through MATE, MATE simulator and the predicted SINR, where different values of parameter A were explored. This is to investigate how its change effects the fitting to the practical measurement and hence the SINR definition. For low SINR small differences were observed, which may be related to non-linear behaviour of the system, for medium SINR the results are in good agreement, for high SINR the measurement systems, and thereby the simulator, are limited by the thermal noise floor.

Traceable metrology of nonlinearity

Top-level achievement summary:

Nonlinear parameter characterisation of hardware and components play an important role for achieving energy efficiency 5G communication systems. The development of 5G systems is made complicated by the nonlinearities introduced when developing highly efficient microwave components for the wireless industry. Supporting metrology for traceable nonlinearity measurement and the correspondent behavioural simulation models are needed.

A variety of strategies will be required to achieve the high levels of efficiency and areal information density that will be required for future 5G systems. These will include power-efficient amplifiers and signal coding and processing for MIMO but ultimately, the linearity and the efficiency of the RF system will define the practical limits beyond which the baseband processing will be ineffective. It is normal practice to compensate for low levels of nonlinearity by using pre-distortion, requiring additional baseband processing of the modulated waveform. As the bandwidth and number of concurrent signals increases, this solution will attract increased OPEX (operational expenditure) for the baseband processing. The design of high-efficiency large signal amplifiers will require supporting large signal models and design tools and these must be supported by traceable and robust large-signal device measurement.

For mobile RF communications it has always been important to be able to measure the RF performance of everything from components to sub-systems. For linear RF components this has traditionally been done with vector network analysers (VNAs) and using vector spectrum analysers (VSAs) and dedicated communications test equipment for the UE and BS equipment. The complexity of the modulation schemes has increased with each successive system generation (2/GSM, 3/UMTS and 4/LTE). This gives rise to more complex power amplifier (PA) designs (e.g. Doherty and Envelope tracking) to service the increased Peak-to-Average Power Ratio (PAPR) and energy demand. Testing requires complex waveforms with similar statistical properties to the native signal. For this reason VNAs are inadequate for this complex measurement task. For the past 10 years different kinds of non-linear vector network analysers (NVNAs) have been launched but their traceability is still an open topic. Device and component models are currently created using large signal network analyser (LSNA) measurements or circuit simulations, yet the metrological traceability of measurements and behavioural models has not been sufficiently solved. In addition different wide-band network analyser measurement systems have been proposed to enable network analyser measurements using realistic test signals (having the correct waveform and statistics).

The aim here was to develop methods for establishing the quality of wide-band measurement systems and for demonstrating the quality of nonlinear measurements made using commercially available NVNAs and LSNAs over a wide frequency range.

Throughout this project, useful measurement methods and simulation tools for establishing the quality of wide-band measurement systems have been developed by NPL, RISI, CMI, SURREY, and Chalmers where Keysight DK and Anritsu had loaned equipment to support the measurements. 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 nonlinear measurement campaign using a nonlinear 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. This objective has been successfully achieved. The developed measurement methods and software tools has influenced how characterization of future 5G components and devices are 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.

Microwave measurement architectures for wideband characterization have been developed and tested for both low GHz and millimeter-wave (mm-wave) operation. A simulation test bench that accurately represents the wideband measurement system and the complete measurements and calibration procedure is developed. This test bench can be useful in simulating other similar measurement system and it is also used to carry out energy efficiency simulation of an amplifier which is also measured using two measurement systems, one at NPL and one at Chalmers. The amplifier measurement campaign between NPL and Chalmers enabled a comparison and validation of the results from two different measurements systems.

To overcome the demand of high data throughput for 5G, wideband communication signals at higher carrier frequency (f_c) is necessary. Carrier frequency below 6 GHz provides large range coverage for mobile communication (e.g. IoT) while above 6 GHz up to the millimetre wave range provides high speed connectivity for short range communication (e.g. indoor communications).

Earlier generations of mobile communication focussed on spectral efficiency but in 5G this must also be balanced against cost and energy efficiency. Achieving energy efficiency is a multifaceted problem because of the nonlinearity introduced by the highly efficient microwave devices and components. Currently, nonlinear measurements are made by changing the output load impedance seen by the device under test using a NVNA. This approach may no longer be practical for the range of frequencies and ultra-wide bandwidths that are proposed targets for 5G.

Strategy and approaches:

This technical objective has been divided into two parts:

1. *Metrology for Wide Band Measurement Systems:*
   1.1. Construction of wideband measurement setup for millimetre-wave frequency
   1.2. Development of simulation model
   1.3. Comparison of measurements and uncertainty results
2. *Traceability for nonlinear measurement:*
   2.1. Comparison of different methods for evaluating the uncertainty
   2.2. Consideration of the sources of error in an NVNA measurements
   2.3. Use of a Monte-Carlo method to propagate uncertainty into an X-parameter behavioural model
   2.4. Inter-comparison of NVNA measurements

Metrology for Wide Band Measurement Systems:

- Construction of wideband measurement setup for millimetre-wave frequency based on Anritsu VNA (MS4640B with wideband digitizer option).
- Development of simulation model components to be used in the CWMS (Chalmers wideband measurement system) based on the Anritsu MS4640B and develop simulation model components of standards and device under test (DUT) to be used in simulation of a complete calibration and measurement procedure.
- Comparison of measurements and uncertainty results of an amplifier measured using CWMS and traceable waveform metrology measurements. The simulation test bench will be also used to simulate the amplifier energy efficiency.

Most of the cited tasks above have been completed by using Chalmers' Massive multiple-input-multiple-output Testbed (MATE) system (see Table 1) and simulator. Chalmers MIMO testbed has been used to construct a one port VNA like architecture. The uncertainties of the measurement system were studied by full Monte Carlo simulations modifying the developed MATE simulator. The results shown in Table 2 demonstrate that MATE can operate also as VNA.

Table 1. KEY FEATURE OF THE MATE TESTBED MATE

Operating frequency	28 – 31 GHz
Analog Bandwidth per TX/RX chain	1 GHz
No. TX	8 (extendable to 16)
No. RX	1 or 2 (extendable to 9)
No. FPGAs (Field-Programmable Gate Arrays)	18
RF Output power per TX chain	Max. -4 dBm
Noise figure RX	3 dB[a]

a From datasheet

Simulation results, using MATE simulator as VNA, of open, short and load standards show a quite good agreement with the measured data. The open, short and load standards were simulated at 28.4 GHz. The raw simulated data were error corrected (calibrated) by using the one port standard calibration procedure developed for VNAs. In Table III the simulated short shows very good agreement with the measured short, meaning that the “MATE simulator as VNA” nicely reproduce the “MATE as VNA” measurement setup.

Table 2. Comparison between simulated and measured results

Short_simulated Raw data	Short_simulated calibrated	Short_measured
-1.0083 - 0.240*j	0.547 - 0.790*j	0.5590-0.8244*j

Monte Carlo simulations of the short standard were performed by implementing noise variation in MATE simulator. It is possible to quantify how the simulated short is influenced when the noise variation is implemented in the simulator. Other sources of uncertainty that influence the measurements, e.g. connection repeatability, uncertainty of standards, temperature variation, vibration, etc. were also implemented in the MATE simulator. The simulated results are compared with the measured data of the same device. Similar drift behaviour is observed indicating that the implementations of the source of uncertainty in the simulator nicely reproduce the real condition during the measurements.

Several amplifiers were measured at both low GHz frequencies as well as mm-wave frequencies. A comparison at mm-wave frequencies was made between a measurement system from NPL and a measurement system from Chalmers.

One of the amplifiers was measured at 2.14 GHz with a wideband calibrated measurement system. The system was calibrated using open, short and load standards as well as a power meter and phase reference, using the developed full traceable method. The system was subsequently used to study the effect of coupling between amplifiers used in developed mm-wave MIMO testbeds.

Coupling between amplifiers in array systems create a load pull like effect on the individual amplifiers. Contrary to existing load pull systems, this is a time-varying effect. We constructed a measurement system that can properly re-create this time-varying load pulling. A modulated signal was applied to the DUT and the influence of coupling was studied by varying the coupling level over some realistic levels. It was shown that ACPR (Adjacent Channel Power Ratio), EVM (Error Vector Magnitude), efficiency and BER (Bit Error Rate) degrade as function of this coupling level. We have both demonstrated direct measurements of these effects, as well as a load pull like technique that can emulate these coupling effects. Verification measurements show good agreement between measurements and emulation.

The traceable, calibrated measurement methods for waveform metrology were also verified at mm-wave frequencies. A two-tone waveform was chosen by the partners as the traceable waveform to be investigated. The device under test was a 28 GHz test and measurement amplifier provided by Chalmers. The two measurement systems are NPLs mm-wave testbed and Chalmers MATE mm-wave testbed.

Both system was calibrated and verified. Measurements at the same input power levels for the DUT were performed. A significant difference between the two measurement systems occurs. It was not possible to further increase the input power, since already at this relative low input power to the amplifier we reached the maximum DC input power allowed to the amplifier. We further investigate this effect by looking at the DC input current as function of RF input power.

Further analysis also shows a significant difference between power consumption between the two measurements. Already for a low input power level, at least 10 dB below the compression level of this amplifier we reach the maximum allowed input current. This implies the input spectrum is not sufficiently clean, for both MATE, as well as the NPL system. Even partly correcting the in-band spectrum (80 MHz for NPL and 1 GHz for MATE) was insufficient to reach sufficiently accurate measurements. Out-of-band signals push the amplifier into its nonlinear domain, resulting in the differences. Improved filtering will be necessary in these systems to reach acceptable results.

Finally, we have demonstrated modelling of power dissipation in amplifiers at low GHz frequencies. The same methodology would have been applied to the mm-wave measurement results. However, the measurements demonstrate the futileness of this approach for these. Even though we can account for in-band effects, many out-of-band effects cannot be quantified and are therefore not available as input to the model.

During the progress and execution of the project, a change in equipment was necessary due to reduced availability of the planned setup. The final solution was to customize an experimental setup designed for

MIMO analysis into a VNA operation, where the reduced measurement capabilities was compensated by a thorough knowledge of the construction of the setup. Since a main outcome is the relevance of the simulations, this change of equipment was beneficial.

<u>Traceability for nonlinear measurement:</u>

<u>Comparison of two different methods for evaluating the uncertainty in input quantities to a measurement model:</u>

Two different methods for evaluating the uncertainty in input quantities to a measurement model have been compared. The two methods, both of which are Type A evaluations of the uncertainty are based on a statistical analysis of a series of repeat observations (i.e. measurements) of one or more input quantities, are as follows:

- the classical method proposed in the guide to the expression of uncertainty in measurement (GUM) and
- the Bayesian method proposed in GUM supplements 1 and 2 (GUM-S1 and GUM-S2).

Two features of the Bayesian method compared to the classical method are that:

- it requires a larger minimum number of repeat measurements of the input quantity (or quantities) – this becomes more pronounced when there are a large number of input quantities,
- it produces a larger estimate of the uncertainty in the input quantity (or quantities).

As an example, consider the measurement of the S parameters of an m-port microwave network fitted with coaxial connectors. An m-port network has m^2 complex valued S parameters which give rise to $N = 2m^2$ real valued input quantities. A minimum of $N + 3 = 2m^2 + 3$ repeat measurements of the S-parameters are required for the Bayesian method to be applicable in which case $m(2m^2 + 3)$ coaxial connections are required and the uncertainty estimated by the Bayesian method is $\sqrt{3}$ times that estimated by the classical method. In the case of a 4-port network, a minimum of 35 repeat measurements of the S-parameters are required involving 140 coaxial connections.

<u>Consideration of the sources of error in an NVNA measurements and the establishment of an uncertainty budget for such measurements.</u>

Some sources of error in an NVNA measurement of amplifier gain were investigated. The error sources considered were:

- System noise;
- DUT (Device Under Test, in this case an Amplifier) connection repeatability;
- Calibration repeatability;
- Choice of calibration method (short-open-load-reciprocal (SOLR), line-reflect-line (LRL) and use of an electronic calibration unit (E-Cal)).

The error sources were investigated by means of repeat measurements of the magnitude and phase of amplifier gain at three harmonics (fundamental, 2nd harmonic and 3rd harmonic) as a function of source power. The magnitude and phase of the mean gain for the three harmonics were calculated as well as the experimental standard deviation of the magnitude and phase of the gain for the three harmonics.

The experimental standard deviation of the gain magnitude for all contributions was on average -60 dB, showing around 20 dB variation between the linear and non-linear operating regimes of the amplifier. The effects of each contribution were generally quite similar, with around 10 to 20 dB variation between them. This variation was greatest in the non-linear operating regime and at harmonic frequencies. When compared to typical amplifier gain figures (around 10 dB), and the variation quoted on datasheets (around 2 dB), the -60 dB average experimental standard deviation due to random error processes measured in this investigation is relatively small. If these processes were to be investigated further, then system noise and connector repeatability would be more beneficial to focus on, as errors from these processes will apply to every measurement of a device and are included in the other contributions.

The experimental standard deviation of the phase of the gain is small at the fundamental, with an average value of around 0.03 degrees across the measured source power range. However, at harmonic frequencies this value increases to around 1 degree for calibration repeatability and different calibration methods. This may be significant for waveform engineering applications where accurate harmonic terminations are critical for achieving the desired device performance. The system noise and connector repeatability contributions for the same conditions are lower, with average values less than 0.5 degrees.

Use of a Monte-Carlo method to propagate uncertainty into an X-parameter behavioural model

X-parameters provide a frequency domain behavioural model of a non-linear device relating the scattered wave Bpm at port p and harmonic m to the incident waves Aqn at port q and harmonic n. It is often sufficient to assume that the only large incident wave is that incident at port 1 of the device at the fundamental frequency with all other incident waves being considered small.

A Monte-Carlo method can be used to investigate the uncertainty of X-parameters due to uncertainty in various independent variables such as the source impedance, load impedance, bias voltage, frequency etc. This can be done for X parameters either measured on an NVNA or calculated from a circuit level design using a circuit simulator.

As an example, the uncertainty in the X-parameters of an amplifier due to uncertainty in the load reflection coefficient was investigated using simulation. X-parameters were calculated in Keysight ADS using the X-parameter generator and harmonic balance simulator. The magnitude of the load reflection coefficient was assigned a truncated normal distribution with a maximum corresponding to zero reflection coefficient and a standard deviation of 0.06 (the normal distribution is truncated because reflection coefficient magnitude cannot be negative). The phase of the load reflection coefficient was assigned a uniform distribution between -180 degrees and 180 degrees. An adaptive Monte Carlo procedure was used in order to estimate the minimum number of trials required and, as a result, 50000 was chosen as a suitable number of trials. A random sample of 50000 load reflection coefficients was generated based on the assigned probability distributions. X-parameters were extracted for the amplifier circuit by considering 3 harmonics which leads to a total of 78 X-parameters of the types XF, XS and XT. The distribution for each X-parameter was built up by calculating the X-parameters for each of the 50000 values of load reflection coefficient.

A comparison of NVNA measurements amongst four of the project participants using two amplifiers and a nonlinear verification device as the DUTs.

A comparison of NVNA measurements was carried out between four organisations (National Physical Laboratory, UK, University of Surrey, UK, Chalmers University of Technology, Sweden and Keysight Technologies, Denmark). The purpose of the comparison was to estimate the typical amount of variability to be expected in measurements of this type and also to help the participants to assess the quality of their measurements.

The three devices under test (DUTs) in the measurement comparison consisted of two amplifiers and a nonlinear verification device (NLVD) all of which were fitted with 3.5 mm coaxial connectors. The two amplifiers were of the same type but the second amplifier had 6 dB attenuators (matching pads) on the input and output. Measurements were made at different fundamental frequencies and power levels. The scattered waves were measured at five harmonics and the gain and power added efficiency of the amplifiers were also measured.

The results obtained showed generally good agreement between the measurements. The variability in the measurements was found to depend on the extent to which the DUT is isolated from the NVNA impedance match conditions with the amplifier with no matching pads showing the most variability and the NLVD (which was specifically designed to be insensitive to the NVNA impedance match) showing the least variability. Some discrepancies in the results highlighted problems with some of the participant's measurements.

Summary and conclusions:

All the objectives have been achieved. The key work and conclusions are identified below:

- Engagement with industry and standards bodies directly (ETSI) and through proxies (3GPP). The data format and terminology and testing approach differs from the standards because the standards are a prescriptive test.
- Scenarios to provide RF power traceability were evaluated. The key issue is dynamic range and this precludes the direct use of a broadband RF power sensor. Either a digital oscilloscope or calibrated VSA must be used. Additional uncertainties will arise from amplification required to reduce the reference

instrument noise-floor. The experimental measurements were conducted at a power level significantly higher than the receiver noise-floor. By exploring the behaviour of the SINR and related parameters we have identified sound traceability strategies. This objective has been achieved.

- Collaboration with the NMI and academic partners provided benefits of background knowledge that is not available within a single institution.
- Collaboration with the industrial partners gave access to equipment that is not available within the NMIs. It also provided a sharper focus on the immediate industrial needs.
- Industry identified narrowband interference as a particular problem. OFDMA coding should mitigate this interference to an extent.
- A series of additional SINR definitions have been developed to suit adjacent channel and mm-Wave scenarios. The relationship between SINR, EVM and CQI has been investigated. Whilst the first two are mathematically related, high EVM values are incorrectly identified without knowledge of the data. i.e. blind evaluation gives the wrong result.
- Simulation studies have shown that low-order QAM signals and interferers are poorly represented by Gaussian noise. Also, simulation studies were carried out for the new SINR definitions. For adjacent channel interference the prediction suggested a larger effect than was found in practice.
- Indoor and outdoor MIMO channel-sounder campaigns were conducted using a new multi-port antenna designed for the purpose. Simulated and measured SINR show good agreement.
- Analysis of the results is highly dependent on commercial software, which is expensive to purchase and maintain.
- Evaluation of the in-band and adjacent channel interference scenarios showed that to achieve the same EVM (20%) the adjacent-channel power needed to be 25 dB higher than the in-channel interference. This infers that at low frequencies the receiver design is more robust so this definition may not apply.
- Mobile phone testers, a key instrument in manufacture and test, were used with a commercial UE device to provide realistic cabled tests. This system has good reproducibility and allowed evaluation of EVM, CQI and data throughput. The results suggest that CQI, although a coarsely scaled measure, is determined directly from the data, and is possibly a more accurate metric.
- Three novel 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.
- 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.
- 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.
- Verify and apply changes to SINR definition for 5G communication, where applicable. A 5G waveform candidate has been employed. Based on the measurement findings, the SINR definition has been assessed and validated.
- 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. This is useful in the development of future 5G characterization equipment and verification procedures.
- A new non-linear measurement campaign using a non-linear vector network analyser (NVNA) on downconverters has been carried out.
- A new commercial non-linear device measurement service has been introduced.

- An inter-comparison exercise has been successfully carried out between participating partners over several amplifiers, which operate as nonlinear devices under tests.

5 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.

6 List of publications

1. T. H. Loh and W. Qi, "A comparison of MIMO antenna efficiency measurements performed in Anechoic Chamber and Reverberation Chamber", *the 85th ARFTG Microwave Measurement Conference (ARFTG 2015)*, Phoenix, Arizona, USA, 22nd May 2015.

2. N. Ridler, and M. Salter, "Analyzing uncertainty matrices associated with multiple S-parameter measurements", *the 85th ARFTG Microwave Measurement Conference (ARFTG 2015)*, Phoenix, Arizona, USA, 22nd May 2015.
3. L. Stant, P. Aaen, and N. Ridler, "Comparing methods for evaluating measurement uncertainty given in the JCGM 'Evaluation of Measurement Data' documents", *Measurement*, Vol. 94, Dec. 2016, pp. 847–851.
4. T. H. Loh, D. Cheadle and P. Miller, "A Millimeter Wave MIMO Testbed for 5G Communications", *the 89th ARFTG Microwave Measurement Conference (ARFTG 2017)*, Honolulu, Hawaii, USA, 9th Jun. 2017.
5. S. Gustafsson, M. Thorsell, K. Buisman, and C. Fager, "Vector-corrected Nonlinear Multi-port IQ-mixer Characterization using Modulated Signals", *the 89th ARFTG Microwave Measurement Conference (ARFTG 2017)*, Honolulu, Hawaii, USA, 9th Jun. 2017.
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