COST Action CA15104
Deliverable 8
New Metrics for
Over-The-Air Testing

COST Action CA15104 (IRACON) aims to achieve scientific networking and cooperation in novel design and analysis methods for 5G, and beyond-5G, radio communication networks.

The goal of EWG OTA is to investigate and validate new OTA testing methods, channel models (in coordination with DWG1) for implementation in advanced OTA testing set-ups for inclusive networks.

This Deliverable reports on the metrics that have been proposed in the Experimental Working Group and the interaction with 5G standardising bodies on these metrics.

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List of acronyms

2D	Two-dimensional
2G	Second Generation mobile systems
3D	Three-dimensional
3G	Third Generation mobile systems
3GPP	Third Generation Partnership Project
4G	Fourth Generation mobile systems
5G	Fifth Generation mobile systems
CTIA	Cellular Telecommunications Industry Association (USA)
DuT	Device-under-Test
DWG	Disciplinary Working Group
EWG	Experimental Working Group
FR1	Frequency Range 1 (in 5G context: up to 7.125 GHz)
FR2	Frequency Range 2 (in 5G context: mmWaves 24.25 – 52.6 GHz)
LoS	Line-of-Sight
LTE	Long-Term Evolution
MIMO	Multiple Input Multiple Output
MPAC	Multi-probe Anechoic Chamber
mmWaves	millimetre waves
OTA	Over-the-Air
RAN	Radio Access Network
RF	Radio Frequency
TD	Temporary Document
WG	Working Group

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1. Introduction

1.1 On the Experimental Working Group-OTA

The goal of the Experimental Working Group on Over-The-Air testing is to investigate and validate new OTA testing methods, channel models (in coordination with DWG1) for implementation in advanced OTA testing set-ups for inclusive networks (large objects, small ad-hoc networks, adaptive networks, etc.).

The WG-specific deliverables are new metrics for OTA testing, after their evaluation in the round-robin experiments; technical inputs and liaison statement(s) to standardisation groups.

1.2 Scientific Tasks of EWG-OTA

The scientific objectives for EWG-OTA are described in four tasks:

Task O-1: Identification of scientific and technical challenges and concerted establishment of goals;

Task O-2: Design, jointly with DWG1, of channel models for implementation in advanced OTA testing set-ups for inclusive networks (large objects, small ad-hoc networks, adaptive networks, etc.);

Task O-3: Development of advanced metrics for device and system performance

Task O-4: Experimental determination of the required degree of sophistication of models, metrics, and implementations, in line with current standardisation.

The achievements with respect to each individual task will be described in the next Section.

2. Results achieved in EWG-OTA

The resonance amongst the proposers of the Action regarding OTA themes to be incorporated in the Action was continued in good participation in the sessions of the EWG OTA. However, the actual number of contributions stayed below expectation. A few research institutes and industries supplied the bulk of the contributions. Interaction with standardisation proved to be difficult, effectively taken care of by EWG-participants that regularly attend standardisation meetings. Nevertheless, a useful contribution to 3GPP RAN4 for the standardisation of 5G was handed in.

2.1 Task O-1: identification of scientific and technical challenges and concerted establishment of goals

The primary OTA challenge identified during the action was the need to address the continued sophistication of the exploitation of the spatial domain through massive MIMO and the move to mmWave frequencies. In particular, the problem domain from 4G is compounded by spatially dynamic operating environments resulting from mobility in the context of active antenna systems. Due to the complexity of this subject and the pressure to complete the 5G specifications, the 3GPP Release 15 – the first full set of standards for 5G New Radio – did not develop specifications to address aspects related to spatial dynamics. The complexity of the system combined with the lack of knowledge of the spatial dynamics of the actual propagation posed such problems that 3GPP was left no other choice than to postpone the handling of mobility to future releases.

An additional problem that had to be faced is that of test systems of completely new designs in very expensive technology, with a lot of RF problems to solve, f.i., coherency, phase noise, receiver noise, output power. It is difficult to commit much money and implementation effort to a test system that is not guaranteed to be suited to future tasks, given the uncertainty in standardisation, apart from being able to gather the funds. The latter will remain a general problem, in view of the costs of hi-tech equipment, in case research institutes can only dispose of local funds instead of supra-national funding like the European Framework Programmes.

2.2 Task O-2: Co-design with DWG1 of channel models

The action reported a number of papers that identified operating environments where the dynamic direction of signals was of import. However, no formal model for spatial dynamics has yet been proposed. EWG OTA contacted DWG1 on channel models but both groups struggled with the common problem of a lack of measurements for the highly directive links to be used in 5G Frequency Range 2.

Earlier measurement campaigns for 2G, 3G, and 4G system development were performed in the context of large projects of the Framework Programmes 5, 6, and 7 that supplied resources for these campaigns. During these programmes, the frequency band of interest did not change significantly, merely the measurement bandwidth was gradually increased as was the complexity of the scenarios. Very few of such projects were granted under Horizon 2020 due to the changed scope of this programme. In the meantime, completely new measurement equipment is required. The frequency bands are now mmWave-bands that require large investments, apart from the much-increased complexity in terms of the number of parallel channels. In that sense, the problems in measuring, describing 5G-relevant scenarios and recreating (emulating) these scenarios are very similar.

But not only experimenters struggle with this. The enormity of the problem in moving to massive MIMO and/or mmWave in 5G has meant standardisation is dealing with the very basics of connectivity and has not had time to focus on the spatial dynamic consequences of how the system will behave or be specified and validated other than in LoS scenarios.

That does not mean no progress has been made at all. Apart from making educated guesses at channel dynamics, due to lack of supporting channel models, the work concentrated on specifying known demands future 5G equipment could put on test systems in order to provide some baseline. It seems rather certain that antenna arrays will be deployed with high antenna element counts and consequentially large electrical apertures. The larger the apertures of the DuT, the larger the resources required for accurate scenario emulation. Additionally, field emulation should be extended to 3D, from the 2D arrangements for LTE in 4G, necessitating another enlargement of test system resources. Apart from these evolutions of techniques for 4G, a novel OTA test method was proposed based on the reflective properties of elliptical cylinders. Such an environment would be capable of emulating multiple spatially dynamic LoS signals.

2.3 Task O-3: Development of advanced metrics for device and system performance

The substance of this task is the subject of this deliverable and it will be detailed further in the next Chapter. One input has been delivered to standardisation (3GPP RAN4), but on the basis of educated guessing, in an attempt to bring standardisation forward. However, by lack of direction regarding test requirements in standardisation, a liaison statement could not be issued and the referred input has not been submitted from IRACON. The stage in which round-robin experiments could be performed was not reached. Apart from the problem of lacking functional OTA systems resulting from missing specifications, 5G-compatible devices were also not available. Work to address the gaps in the specifications is being carried out in 3GPP Release 16, but even this release will not fully develop the spatially dynamic requirements needed to motivate the development of test systems.

The new metrics proposed in EWG OTA are predominantly meant for evaluating the performance of practical OTA test environments vs. ideal environments that are impractical to implement. No specific metrics were developed for device and system performance, as explained in the foregoing Section.

2.4 Task O-4: Experimental determination of the required degree of sophistication of models, metrics, and implementations, in line with current standardisation

Most simulation and measurement campaigns predict a sparse channel at mmWave frequencies, that is, considering the highly directive antenna arrays required for maintaining viable link budgets at these high frequencies. This indicates that test environments should consist of a low number of simultaneous spatially dynamic signals, which would be favourable regarding the amount of emulation resources. By lack of proper models, as mentioned in Section 2.1, the temporal and spatial dynamics are still unresolved as well as how sparse the channel actually is as this also depends on actual array configurations. As regards lining up the activity in the Action with current standardisation, even active 3GPP members were unable to gain traction to move spatially dynamic themes forwards in 3GPP, so, in hindsight, inputs from outside bodies would not have helped although IRACON did so once. CTIA did start a 5G group but it is focussed on more basic LoS connectivity issues than advanced OTA metrics.

3. Metrics

3.1 Introduction

The standardisation process for MIMO OTA testing agreed to use Absolute Data Throughput as the primary metric. This metric is tightly coupled to the theoretical limits of LTE transmission modes and as such linked to the LTE system and its performance under various channel conditions. For 5G New Radio, a similar concept could be used, but an urge exists to investigate the primary reception process with respective channels for 5G New Radio, before assessing conformance to standardised benchmarks. What is meant here is that neither a well-defined system design has been available from the start of the IRACON Action onwards, nor are the channel characteristics well understood, especially for Frequency Range 2 with the intended beam-steering mode. As a result, it makes sense to concentrate first on how well antenna arrays point their beams and with what agility. The communication process is then understood to be combining transmit and receive arrays to links that are subjected to realistic channels. That is, channels in which various scattering objects alter directions of beams depending on actual positions of transmitter and receiver, potentially scattering beams away from the receiver. This channel behaviour is substantially different from traditional spatio-temporal mobile radio channels (i.e., for up to 4G systems) because the radio environment is "illuminated" in a much more confined way, lacking the averaging effect of the angularly much wider Base Station antenna patterns. Otherwise, the radio environment itself is grossly speaking very similar. Of course, the shift up in frequency from FR1 to FR2 has influence on the scattering properties of environments, but in the course of the IRACON Action (here we refer to the reports of Disciplinary Working Group 1 on Radio Channels) it became clear that these differences are not necessarily dramatic. The much sparser scattering reported earlier for FR2 is likely to be caused by the use of "pencil beams" in the measurement campaigns. Nevertheless, the degree of detail to which the channels have to be modelled for employment of beam-steering is not reached yet.

3.2 Activities in EWG OTA towards metrics

Apart from making educated guesses on channel characteristics in beam-steering applications, the approach in EWG OTA has been to search for alternatives to the Wave Field Synthesis approach of radio environment emulation for MIMO OTA. Such emulation can take place in so-called MPACs or in Radiated Two-Stage set-ups, but scaling these test systems from FR1 to FR2 is not viable, not to mention that the MPACs should be expanded from 2-D to 3-D as well. One of the promising proposals for simpler test installations is the sectored MPAC with the restricted solid angle it covers compared to the 4π of a full 3-D system. Other proposals aim at developing ways to save on the expensive drive electronics by using switching matrices, and using sparse detection techniques. A complete different emulation principle was recently introduced. Instead of using distributed sources for generating the power angular spectrum, a central illuminator is used whose radiation is directed to the DuT by an ellipsoid system of mirrors. Despite reducing the amount of electronics in all of these systems, it remains a hindrance that the specialised electronics for FR2 are very expensive compared to FR1.

3.3 Metrics developed in EWG OTA

A number of new metrics are presented in IRACON. As mentioned before, the input to EWG OTA concentrated on assessing to which extent test systems are fit for yielding a specified (dynamic) power angular spectrum. This is reflected in the first six metrics that assess aspects of test system accuracy. The seventh metric is the only one that considers the DuT. It measures Base Station output power and antenna array integrity, specifically aiming at massive arrays.

The metrics are

1. Total Variation Distance of the Power Angular Spectrum
2. Power Angular Spectrum Similarity Percentage
3. (Weighted) Spatial Correlation Error
4. Beam peak distance
5. Total Variation Distance of Beam Allocation Distributions
6. Fixed-Beam Power Loss
7. Capacity Loss

We will discuss them one by one.

All these metrics target FR2, but could also be used for FR1, when similar operational conditions apply. The last three are specifically targeting beam-forming DuTs with pre-defined directions from a code book. Note, for applying the metrics, the directions need not be known. Metric no.1, no.3, and no.4 are proposed to 3GPP in document R4-1705831.

ad 1.

With respect to the first metric, the Total Variation Distance of the Power Angular Spectrum assesses how well the OTA system reconstructs a reference composite Power-Angular Spectrum with a limited number of OTA antennas and restricted range length. An important point is that the PAS is evaluated with the resolution of the DuT based on the antenna array size and/or aperture, effectively taking some angular averaging into account.

ad 2.

The second metric, Power Angular Spectrum Similarity Percentage, is very similar to the first, but the scaling is not to a dimensionless distance between 0 and 1 but to a percentage between 0 and 100%. This can prove convenient in some applications.

ad 3.

The third metric, the Weighted Spatial Correlation Error, does consider the limited resolution aperture of DuTs, but is otherwise the same as used for Wave-Field Synthesis in FR1. Spatial correlation is an important factor in diversity or multiplexing gain in MIMO links and as such, is also of importance for 5G communication devices.

ad 4.

Beam peak distance, the fourth metric, assesses beam-steering accuracy as the angular distance (in degrees) between probability weighted average directions of the allocated beams. However, this formulation makes it sensitive to small changes in the reconstructed discrete PAS in the case of many clusters of similar power, possibly resulting in inconsistent outcomes.

ad 5.

Total Variation Distance of Beam Allocation Distributions, as number five in the list, is a beam selection metric with a specific justification. In the mode of operation assumed for 5G devices, the DuT transmits through fixed beams (each with a pre-defined direction) from a discrete code book of antenna weights. The operational beam is selected through sequentially scanning all beams for highest power, taking into account the angular spreading in the channel. The metric evaluates how the measured angular power distribution deviates from the reference one.

ad 6.

Fixed-Beam Power Loss quantifies the influence of the distance from transmit array to receive array on the gain of the transmit array. This, of course, considers the finite size of (anechoic) testing chambers. For distances not too far below the Fraunhofer distance, the array pattern does not necessarily deviate from the far-field pattern, but the array gain is less since it is not yet fully developed. How much less is described by this metric.

ad 7.

The previous six metrics apply to advanced OTA systems in anechoic chambers. However, even very basic parameters have to be measured OTA for new system designs, making reverberation chambers a possible solution for simple metrics. Methods based on reverberation chambers have not been selected for MIMO OTA testing as spatio-temporal channels cannot sufficiently accurately be emulated. But, reverberation chambers are intrinsically well-suited for measuring power, an important parameter in any communication link. The metric Capacity Loss was introduced to quantify the effect of deficient antenna elements on the downlink performance multi-user Massive MIMO narrowband systems, stated in terms of loss of downlink ergodic sum rate in a single cell. The channels used are not very realistic, Rich Isotropic MultiPath (RIMP) and Random Line-of-Sight (Random-LoS) channels, but these can be reproduced in stirred-mode reverberation chambers.

3.4 Correspondence of metrics and Temporary Documents

In Table 1 below, we list the correspondence between the metrics discussed above and Temporary Documents in IRACON. References to these metrics in open literature are also given.

Table 1

Metric	Test setting	Source	Authors
Total variation distance of PAS	Anechoic room	TD(17)04061, [1], [2]	P. Kyösti, L. Hentilä, A. Hekkala, M. Rumney
PAS similarity percentage	Anechoic room	TD(19)09058, [1]	P. Kyösti, P. Heino
Beam peak distance	Anechoic room	TD(17)04061, [1], [2]	P. Kyösti, L. Hentilä, A. Hekkala, M. Rumney
Fixed-Beam Power Loss	Anechoic room	TD(17)03015, [3]	P. Kyösti, W. Fan , J. Kyröläinen
Total Variation Distance of Beam Allocation Distributions	Anechoic room	TD(18)06035, [2]	P. Kyösti, L. Hentilä, J. Kyröläinen, F. Zhang, W. Fan, M. Latva-aho
Spatial correlation error	Anechoic room	TD(17)04061, [1], [2]	P. Kyösti, L. Hentilä, A. Hekkala, M. Rumney
Capacity loss	Reverberation chamber	TD(19)10023, [4]	A.A. Glazunov

4. Conclusions and Perspectives

4.1 Conclusions

One contribution on metrics has been submitted to standardisation (3GPP RAN4), be it not under the name of IRACON as no formal liaison exists. The metrics described assess test equipment capabilities, rather than equipment performance, like most of the metrics proposed in EWG OTA. One proposed metric targets actual system hardware performance. This result does not match the expectations that were expressed at the start of IRACON. At the outset of IRACON, prior to the completion of the 3GPP 5G specifications, there was awareness of the considerable increase in complexity that would arise from the introduction of massive MIMO, active antenna systems, and mmWave frequencies. However, the challenge in moving to active antenna systems and higher frequencies created a problem domain that exceeded the ability of 3GPP to deal with during the time frame of IRACON. As a result, 3GPP only addressed the most basic of OTA connectivity for spatially static Line-of-Sight links, and the far more complicated and nuanced challenges of multiple simultaneous spatially dynamic links have barely been investigated. Therefore, no meaningful resources were applied to the more difficult spatial issues posed by active antenna systems and mmWave frequencies. Although these challenges are real and will directly impact the performance of 5G systems, they have not been addressed by 3GPP or IRACON and remain open issues to be resolved in the future.

4.2 Perspectives

With IRACON ending in March 2020 and only one meeting left, EWG OTA will not be able to significantly expand the present suite of metrics. The perspective of other organisations achieving more extensive results mainly depends on the development of the critical channel models and on standardisation producing a viable system concept for terminal mobility under beamsteering conditions in FR2 for 5G, let alone the testing concept for such conditions. For channel models, pertinent measurement data are simply missing. Without concerted actions to acquire these data, for which large resources will be required, progress will be slow. Forecasting how future progress in standardisation will be is beyond our competence. Apart from these obstacles, other difficult problems regarding test environments remain to be solved, like the handling of active antenna systems or a really 3D emulation with sufficient angular resolution. But, especially with the latter aspect, IRACON EWG OTA provided new concepts that are a good basis for future developments.

5. References:

[1] R4-1705831 to 3GPP-RAN4, Keysight, "Metrics for evaluating RRM/Demodulation Measurement Setup", Hangzhou, China, May 2017.

[2] P. Kyösti, L. Hentilä, W. Fan, J. Lehtomäki, and M. Latva-Aho, „On Radiated Performance Evaluation of Massive MIMO Devices in Multiprobe Anechoic Chamber OTA Setups", IEEE Transactions On Antennas And Propagation, Vol. 66, No. 10, October 2018.

[3] P. Kyösti, W. Fan, and J. Kyröläinen, "Assessing measurement distances for OTA testing of massive MIMO base station at 28 GHz", EUCAP, Mar. 2017, pp. 3679–3683.

[4] A.A. Glazunov, „Impact of deficient array antenna elements on downlink massive MIMO performance in RIMP and random-LOS channels", EuCAP, 9-13 April 2018, London, UK.