Guest Editorial: Metrology for 5G Technologies

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The next generation communication system, typically referred to as the fifth generation (5G), is currently under global intensive research and development in industry, academia and governmental organisations. The new 5G cellular systems are envisioned to achieve better performance, e.g. higher data rate, better energy efficiency, and higher reliability than current systems. Of the wide palette of 5G features, millimetre wave (mmWave) communication, ultra-wide system bandwidth, and large-scale antenna systems are regarded as essential enabling components.

To make 5G antenna systems a reality, significant effort has been taken to develop effective test and measurement methods to ensure system requirements are properly validated. These include regulatory, conformance and production test requirements. Due to the new 5G antenna technologies, unprecedented challenges for testing have emerged. For sub-6 GHz antenna systems, accessible antenna connectors are typically implemented for cable conducted testing purposes. However, at mmWave frequencies, it is known that conducted testing will no longer be possible due to the lack of antenna connectors and the possibility of large numbers of antenna elements. Furthermore, it is important that test systems can offer high precision and high efficiency (test time) with low system cost. The objective of this Special Section is to address the technical challenges in metrology for 5G.

The testing challenge can be categorised into three main areas; radio frequency (RF) aspects, demodulation performance (throughput) and radio resource management (RRM) which is concerned with access and mobility. Each of these test aspects require different test environments. At sub-6 GHz frequencies, testing has been almost exclusively done using conducted temporary antenna connectors with the exception of a few radiated tests. But at mmWave frequencies all testing will be done using radiated connections. The RF test environment is the easiest to emulate and involves line-of-sight cable replacement techniques using anechoic chambers. This type of testing covers the essential RF characteristics of the system including transmitter and receiver performance including signal quality, unwanted emissions and sensitivity. The demodulation tests where throughput is measured under impaired conditions requires a more complicated test environment including channel emulation to provide temporal and frequency fading, which also extends into the spatial domain. These spatial aspects proved to be a major challenge for sub-6 GHz radiated test systems. Finally, the RRM test aspects present the greatest challenge, since in addition to the multi-cell scenarios in sub-6 GHz environments, the mmWave environment includes the spatial domain where signals will be arriving at multiple dynamic angles of arrival. Existing spatial test systems which were sufficient in the sub-6 GHz era do not scale to mmWave frequencies.

With this background, the papers in this Special Section can be categorised as primarily addressing the RF aspects and some demodulation aspects, but the most complex 5 G metrology challenge of RRM in a 3D spatial environment remains elusive and an ongoing topic for future research. Below we introduce the papers that are accepted to the Special Section.

The anechoic chamber is the predominant selection for shielded enclosure in wireless system testing and is used for RF, demodulation and RRM test aspects. Total radiated power (TRP) is a key RF performance metric in over-the-air (OTA) testing of wireless devices. The paper ‘Shortest range length to measure the total radiated power’ by Derat *et al*., introduces a closed-form expression for the measured power integrated over a surface surrounding the device under test (DUT), including the influence of the probe. Measurements were conducted in two spherical OTA scanners with the same set of antennas. Both modelling and experimetal results confirm the Fraunhofer distance as a lower bound of the range length required to evaluate TRP with an acceptable accuracy, for an OTA system measuring electric field strength only.

Reverberation chambers (RC) have been extensively used for wireless system performance evaluation, in particular for the RF aspects of total radiated power (TRP) and total isotropic sensitivity (TIS) characterisation. The growth of Internet-of-Things (IoT) applications require billions of inexpensive wireless devices with various form factors. Most of the IoT devices have no connectors for testing. Hence, conducted testing is not an option any more. For verification of the complete IoT device, cost-effective and efficient OTA testing techniques are highly desirable. Some important performance metrics (e.g., receiver sensitivity) require establishment of an actual communication link. The RC loaded with lossy absorbers provides an efficient testing environment to measure averaged quantities (such as the TIS) with flexibility in test zone and device form factor, etc. An overview of OTA testing in the RC was presented in the paper ‘Flexibility in over-the-air testing of receiver sensitivity with reverberation chambers’ by Horansky and Remley. The RC measurement results are also compared to the counterparts of anechoic measurements. The flexibility and consistency of the RC based OTA testing technique was demonstrated via extensive measurements of a wireless device in three different RC setups and by comparison to anechoic chamber measurements in the paper.

Measurement uncertainty is an important factor for RC measurements. In the paper ‘Measurement uncertainty of RC and its reduction techniques for OTA tests: a review’ by Chen, an overview of the RC uncertainty is given for OTA applications. Apart from a thorough literature survey, some new results about uncertainty reduction are also presented. Due to the rapid development of automotive industry and smart transportation, the demands for automotive over-the-air (OTA) tests and electromagnetic compatibility (EMC) tests in the RC have attracted considerable attention from both industry and academic. Consequently, it is important to evaluate the performance of the RC loaded by a vehicle under test. Previous research mainly focuses on qualitative evaluation of the RC performance for a static vehicle. In the paper ‘Investigation of automotive testing in a reverberation chamber’ by Xue *et al.*, the idea of using rotated vehicles to reduce the measurement uncertainty is verified through numerical simulations. The results show that the measurement uncertainty can be significantly improved by rotating the vehicle under test using a large turn-table platform, and the larger the volume of the vehicle sweep, the better the improvement is. Moreover, it is found that the restriction of the volume of the vehicle under test can be relaxed (i.e., > 8%) in automotive tests.

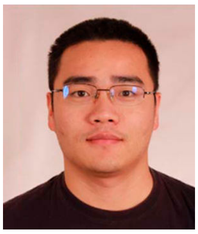
Radio channel modelling is important for wireless system design and performance evaluation. Two papers on this topic are accepted to the Special Section. In ‘Hybrid virtual polarimetric massive MIMO measurements at 1.35 GHz’ by Challita *et al.*, a massive multiple-input multiple-output (MIMO) channel sounder, which is realised by moving an eight-element uniform linear array (ULA) at predefined locations (to form a virtual uniform rectangular array (URA)), It was utilised to measure polarimetric radio channels at 1.35 GHz in an indoor line of sight scenario. The multi-user performance was evaluated using the measured massive MIMO channels. In 'Channel sounding, modelling and characterisation in a large waiting hall of a high-speed railway station at 28 GHz' by Zhao *et al.*, a channel sounding campaign at a large waiting hall of a high speed railway station at 28 GHz was presented. The channel modelling, simulation and validation are performed and compared with the QuaDRiGa simulation platform. The QuaDRiGa simulation results agree well with measurement data, which verifies the applicability of QuaDRiGa in millimeter wave band.

For demodulation testing in spatially controlled environments, a multi-probe anechoic chamber (MPAC) can be used. The physical dimension is a key cost factor in an MPAC system. Radio waves radiated from probe antennas will have a spherical wave front over the test area when using a short range length, which is problematic for channel emulation. To address this problem, a sub-array antenna system, whose element excitations are properly optimised to generate a plane wave, is utilised to replace each probe antenna in the MPAC systems in the paper 'Plane wave compensation technique for multiple-input multiple-output over-the-air testing in small multi-probe anechoic chamber' by Wang *et al*. This proposal is shown to be effective in reducing the MPAC size in numerical simulations in the paper.

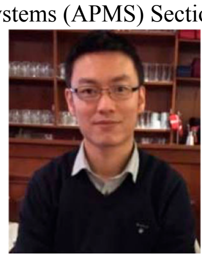
In 'Use one-bit technique to measure the coherence in the time, frequency and space domain in a reverberation chamber' by Xu *et al.*, the one-bit technique is introduced to measure the time domain, frequency domain and space domain correlations in an RC. The one-bit technique will be useful to develop efficiently and low-cost 5 G testbed in the RC.

Recent advancements of backscatter systems for high bit rate IoT communications, have driven the need to develop traceable measurement system for evaluation of optimum IoT link performance. The paper 'Characterisation and implementation of high-order backscatter modulation for IoT applications' by Jordao *et al*., characterises a backscatter modulation system, considering both conducted and radiated tests. Different modulations were characterised where the EVM results was computed.

Guest Editor Biographies

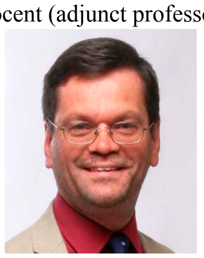


Wei Fan received his Bachelor of Engineering degree from Harbin Institute of technology, China in 2009, Master's double degree with highest honours from Politecnico di Torino, Italy and Grenoble Institute of Technology, France in 2011, and Ph.D. degree from Aalborg University, Denmark in 2014. From February 2011 to August 2011, he was with Intel Mobile Communications, Denmark as a research intern. He conducted a three-month internship at Anite Telecoms oy (now Keysight Technologies), Finland in 2014. His main areas of research are over the air testing of multiple antenna systems, radio channel sounding, modelling and emulation. He is currently an associate professor at the Antennas, Propagation and Millimeter-wave Systems (APMS) Section at Aalborg University.

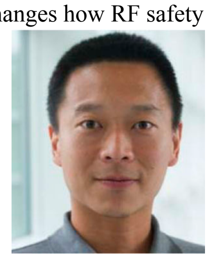


Xiaoming Chen received the B.Sc. degree in electrical engineering from Northwestern Polytechnical University, Xi'an, China, in 2006, and M.Sc. and PhD degrees in electrical engineering from Chalmers University of Technology, Gothenburg, Sweden, in 2007 and 2012, respectively. From 2013 to 2014, he was a postdoctoral researcher at the same university. From 2014 to 2017, he was with Qamcom Research & Technology AB, Gothenburg, Sweden, where he was involved in the EU H2020 5GPPP mmMAGIC project (working on 5G millimeter-wave wireless access techniques). Since 2017, he has been a professor at Xi'an Jiaotong University, Xi'an, China. His research areas include 5G multi-antenna techniques, over-the-air testing, reverberation chambers, and hardware impairments and mitigation. He has co-authored one book, one book chapter, more than 60 journal papers, and over 60 conference papers on these topics. Prof. Chen serves as an Associate Editor (AE) for the journal of *IEEE Antennas and Wireless Propagation Letters* and received the outstanding AE awards in 2018 and 2019. He received the URSI (International Union of Radio Science) Young Scientist Awards in 2017 and 2018.

Pekka Kyösti received the M.Sc. degree in Mathematics and the D.Sc. degree in telecommunications from the University of Oulu, Oulu, Finland. From 1998 to 2002, he was with Nokia Networks, Espoo, Finland. From 2002 to 2016, he was with Elektrobit, Oulu, and Anite Telecoms Oy, Oulu. Since 2002, he has been involved in radio channel measurements, estimation, and modelling. From 2008 to 2012, he was actively developing methods for MIMO over-the-air testing. He was moved to Keysight Technologies Finland Oy, Oulu, along the acquisition in 2016. He is currently involved in channel modelling for 5G systems with Keysight Technologies Finland Oy and with the University of Oulu. He is a senior specialist with Keysight technology and Docent (adjunct professor) with Oulu university.



Moray Rumney received a BSc in EE from Heriot-Watt University in 1984. He joined Hewlett-Packard that year and has remained with the company through the transition to Agilent Technologies in 1999 and Keysight Technologies in 2015. Moray joined ETSI in 1991 and 3GPP in 1999. His recent work has focussed on OTA test methods. He was technical editor and major contributor to Agilent's book "LTE and the Evolution to 4G Wireless". Moray became an independent consultant in 2018 but still represents Keysight at 3PP RAN plenary. His recent focus has been on the growing debate about the safety of the RF radiation from mobile commutations and the way in which 5G technology changes how RF safety limits should be specified and verified.



Tian Hong Loh received a PhD degree in engineering from the University of Warwick, Coventry, United Kingdom in 2005 before joining the UK National Physical Laboratory (NPL) the same year. Tian Hong is a Principal Research Scientist at NPL. He has authored and co-authored over hundred refereed publications, published three book chapters, holds five patents and two best paper awards from international conferences. He is a visiting professor at University of Surrey, visiting industrial fellow at University of Cambridge, and UK representative of Union Radio-Scientifique Internationale (URSI) Commission A (Electromagnetic Metrology) and was coordinating an EU project entitled 'Metrology for 5G Communications', under the European Association of National Metrology Institutes (EURAMET) European Metrology Programme for Innovation and Research (EMPIR). He is an associate editor of *IET Microwaves, Antennas & Propagation (MAP)*, *IET Communications (COMMS)* Journals, associated editor of *URSI radio science bulletin (RSB)* and was the TPC chair of 2017 IEEE International Workshop on Electromagnetics (iWEM 2017).