A NIST Perspective on Metrology and EMC Challenges for 5G and Beyond

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Abstract: Wireless connectivity, the internet of things, smart technologies and applications will all create new EMC challenges, in both expected and unexpected forms. Traceable metrology needs to be developed, both to characterize and optimize these future systems, and to minimize interference and EMC problems. This paper looks at metrology and EMC challenges related to 5G and beyond communications, and what NIST is doing towards solutions.

Introduction

The potential to connect people and devices anywhere and anytime is driving the development and deployment of a multitude of wireless systems. Wireless connectivity is central to advanced communication technologies, the internet of things (IoT), the smart grid and smart homes, next-generation automotive technologies, and smart manufacturing, to name a few examples. This connected future will involve faster modulation rates, higher frequencies, smart antennas, multiple-input, multiple-output (MIMO) links, dynamic spectrum allocation, and more. Supporting these radiated technologies will require advances in fundamental microwave metrology, antenna characterization, and electromagnetic compatibility (EMC) test methods. The complete set of specifications for 5G and beyond systems are yet to be fully defined, as are all the EMC problems that will be encountered. With that caveat, this paper discusses some of the metrology and test needs we expect, and what we at the National Institute of Standards and Technology (NIST) see as the research challenges to meet them. The Communications Technology Laboratory (CTL) at NIST has been created to support the current and emerging metrology needs of communications. CTL-EMC projects are following this evolution, transitioning the EMC focus from digital electronics to communications systems.

This paper starts at the fundamental level of a cabled signal source to a receiver and the metrology needed to traceably calibrate this chain as modulation rates and carrier frequencies rise. Next, extending this chain to a traceable radiated channel, for example in an anechoic chamber, will be fundamental to over-the-air (OTA) test method development. Characterizing more general radiated paths in scattering rich environments will require channel sounders and channel models, and we look at metrology challenges related to accurate channel sounding, particularly at mmWave frequencies. Wireless communications at mmWave frequencies will take advantage of active, multiple-beam antennas and MIMO systems to increase channel capacity and extend range. Such active and multiple-element antennas will require new measurement techniques. Massive arrays based on integrated electronics and digitally synthesized signals pose several calibration challenges. Finally, future spectrum allocation will be made more dynamic while seeking to optimize spectrum usage. In all these measurement areas, uncertainty analyses are needed to quantify system performance and reliability. These analyses are complicated by the complexity of the systems and correlations between uncertainty parameters. To address this problem, NIST has developed a software tool, the NIST Microwave Uncertainty Framework (MUF) that allows us to build uncertainty models of instruments and systems, track correlations, and use Monte Carlo simulations to help estimate uncertainty. This provides a traceability path from fundamental physical quantities (such as the meter, second, and volt) to high-level metrics such as bit-error rate (BER), error vector magnitude (EVM) and RMS delay spread.

Across the above wireless scenarios, interference will need to be minimized and coexistence maximized to achieve the full potential of future dense wireless device systems; thus, EMC models and test methods will be critical to future wireless technology advancement. The challenges are many, but the promise of wireless connectivity is immense.

Calibrated mmWave Modulated Signals: Cabled Source to Receiver

Real communication signals used in wireless systems consist of electrical voltages and currents, or electromagnetic waves. Because these signals pass through real components, distortion is introduced at every step of signal generation, transmission, and reception. The only way to unambiguously characterize this distortion is through measurement, which is why the instrumentation industry plays such a critical role in the telecommunications industry. Because instruments are also composed of real, distortion-producing components themselves, they must be characterized and calibrated, especially at higher frequencies. Calibration of the hardware portion of a wireless signal chain is a fundamental step toward overall traceability for modulated communication signals. New and improved calibrations, measurement techniques, robust uncertainties, and an extended traceability path would be of great value to system designers, instrumentation manufacturers, and practicing engineers.

Signal characterization is challenging at mmWave frequencies because errors in microwave circuits generally scale with frequency; manufacturing tolerances for electronic components that give a few degrees of phase error at today's operating frequencies near 700 MHz become tens of degrees at 7 GHz, and hundreds of degrees at 70 GHz. Because similar types of electronic technology are used for both signal generation and measurement, both suffer from commensurate errors that scale with frequency and must be accurately characterized, and then corrected by use of digital signal processing. These errors include frequency response, impedance effects, interleave errors and other nonlinear effects. These must be characterized to traceably measure a communications signal.

As we have seen in previous work, calibrations at mmWave frequency bands involve correcting for the increasingly non-ideal hardware. Such corrections often require iterative measurements and complicated uncertainty analyses. NIST continues to pioneer the use of such laboratory-based techniques to provide characterized sources and receivers as transfer standards that may be used to calibrate other "real-time" instruments used in the field [1-5]. The calibrated prototype mmWave modulated-signal source shown in Fig. 1 provides measurements that are traceable to primary standards [2, 3]. Because wireless channels rapidly change, signal measurements made in the field must be real-time with a minimum of dead time. Applications of calibrated real-time mmWave signal generation and measurement are myriad [6-13]. Extending this characterization to mmWave bands will provide improved channel sounding and calibrated electromagnetic environment sensing and emulation, all with multi-gigahertz bandwidth.

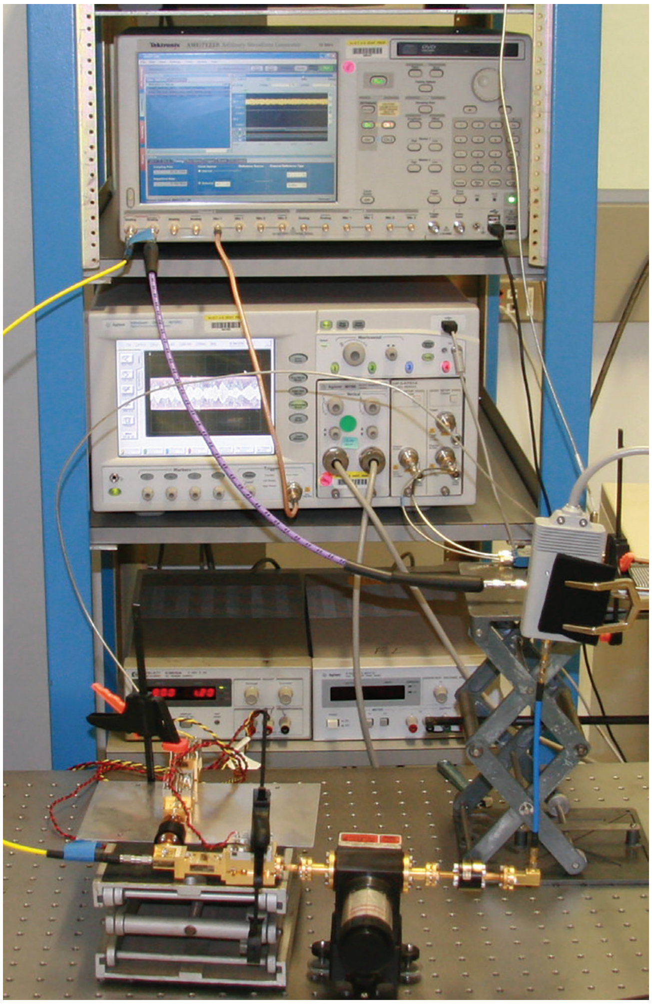

Figure 1: Calibrated millimeter-wave modulated-signal source consisting of an arbitrary waveform generator (top in rack) whose signal is upconverted to mmWave frequencies (on table). Characterization and predistortion of the non-ideal mmWave hardware is carried out by iteratively measuring the waveform with the characterized sampling oscilloscope (bottom in rack), modifying, uploading and remeasuring the waveform. Products are shown for illustrative purposes and does not imply endorsement by NIST. Other products may work as well or better.

In the near term, we see a need for transfer standards based on modulated-signal sources and receivers. For NIST this means continuing our work on developing new calibration methods that extend the NIST traceability path to mmWave frequencies. We are advancing methods to calibrate vector receivers, such as vector signal analyzers, which are complicated because the distortion in the calibration instrument may be comparable to the distortion in the receiver, and the two are not easily separable. We are also working to calibrate multi-gigahertz digitizers by correcting for interleave errors.

Calibrated mmWave Modulated Signals: Radiated Source to Receiver

Future mmWave-OTA tests require that the-signal-source-to-receiver traceability path discussed above be extended to include a radiated channel. Providing a known, calibrated, modulated field at a specific location in space will allow industry to compare the reported received-signal levels of their devices under test (DUT) with known values. NIST is developing a traceability path from the mmWave signal source discussed above to an arbitrary free-field test location in our fully anechoic chamber. The uncertainties corresponding to our calibrated reference antennas, such as the one shown in Figure 2, will be combined with the uncertainties from the mmWave modulated signal source (and the characterized receiver) to provide full traceability at a location in free space.

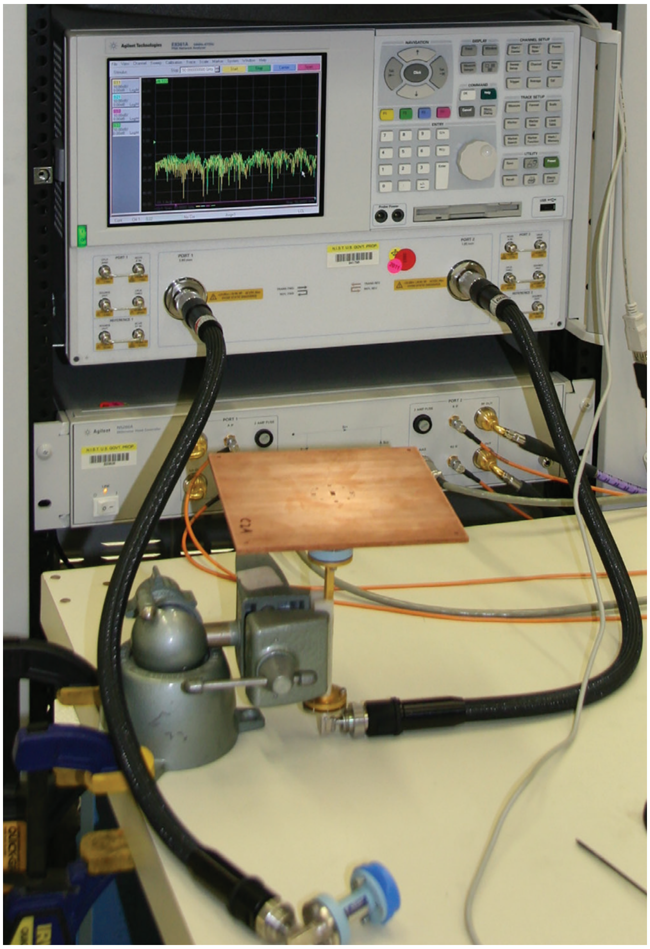

Figure 2: Characterization of an open-ended waveguide with plate [60] for traceable free-field measurements of modulated signals.

In support of this work, NIST is upgrading its anechoic chamber positioning system to integrate a six-degree-of-freedom industrial robot placed on a floor-mounted rail. This system will position DUTs in the chamber to enable much greater accuracy in alignment and scans, as well significantly reducing the set-up time. Once implemented, NIST will perform extensive extrapolation measurements over a number of bands from several hundred MHz to mmWave frequencies which will accurately capture modulated field strength in the far-field and quasi-far field of our set of source antennas (open-ended waveguide and standard gain horns).

Verifying field strength also presents challenges. Calibrated probes require a known field, but to accurately know a field requires a calibrated probe. One possible solution to this problem is to use a quantum based probe directly linked to the International System of Units, or SI. NIST is pursuing this approach using Rydberg atoms as an RF-to-optical transducer with direct SI traceability [14-17]. The long-term goal is a self-calibrating field probe on a chip that can be integrated into instrumentation, and wireless devices and systems, see Figure 3.

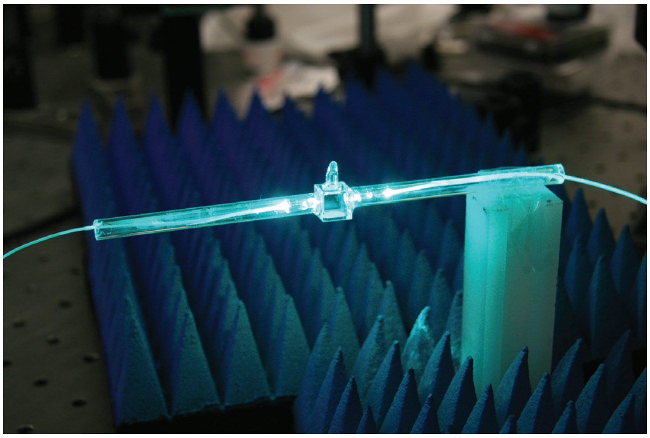

Figure 3: The first fiber-coupled vapor cell for self-calibrated E-field measurements over a large frequency band including 500 MHz to 500 GHz (and possibly up to 1 THz and down to tens of megahertz).

A further challenge to establishing traceability for modulated fields is an uncertainty analysis that captures the nonidealities throughout the signal chain. NIST is using the MUF to estimate uncertainties for near-field based extrapolation antenna gain measurements that will describe the modulated fields at specific locations in the anechoic chamber. A remaining challenge is to accurately capture systematic effects, such as room scattering and mutual coupling. This uncertainty work will help to quantify real-world effects that must be addressed before EMC and related standards can be developed, such as the effect of measuring error vector magnitude off the main axis of the antenna beam. Single input, single output (SISO) work that characterizes both spatial domain and electronic distortion, is an important first step toward similar goals for MIMO systems and antenna arrays.

Modulated Signals in Reverberation Chambers

Traceable measurements of modulated fields in an anechoic chamber will be important for mmWave OTA testing of common wireless metrics such as radiated power and receiver sensitivity in isotropic environments. NIST is also researching techniques for extending the current cellular-band use of reverberation chambers for these tests [18-19] to mmWave bands [20-21], as well as reverberation chamber tests to simulate multipath environments. A typical set-up is shown in Figure 4.

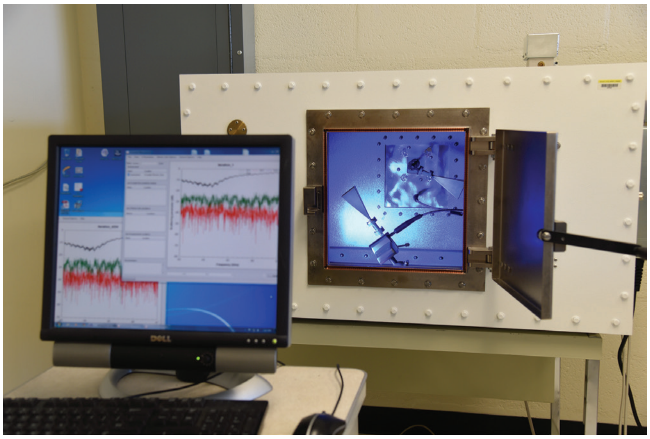

Figure 4: Reverberation chamber set-up for measuring modulated signals at 45 GHz.

Reverberation chambers are an important tool for EMC evaluations with narrowband signals. However, EMC and OTA evaluations with broadband signals are much more complicated. Narrow coherence bandwidths of an empty chamber create difficulties in maintaining a communications link. To deal with this, RF absorber is often added to the chamber, which increases the coherence bandwidth and reduces the chance that a link must be reestablished. However, much of reverberation chamber theory depends on the highly-reflective characteristics of the chamber. NIST research is focusing on determining how much absorber can be added to a chamber and still use generalized results of the theory. In addition, further evaluations of the interactions between a broadband modulated source, a reverberation chamber, and possible interference victim equipment should be done to see how best to use such chambers for broadband EMC.

With broadband communication systems, even defining failure for an EMC test can be complicated. Link failures can be extreme examples of interference. But with modern error detection and correction methods, the robustness of communications links continues to improve. However, even if the link is maintained, interfering signals will still cause some degradation of the signal. But what parameters indicate degradation? Is it sufficient to monitor BER and EVM, or is throughput or some other key performance indicator more appropriate? And how will limits be set? With limited spectrum, the interference victim may need restrictions on the problematic emissions, but those restrictions can negatively impact the performance of the emitting system. To make matters worse, both systems can be operating within existing standards and still cause problems. For these reasons, defining and accurately measuring key performance indicators and then adjudicating between competing spectrum users will be one of the greater challenges for EMC.

Channel Sounder Metrology

Radio-frequency channel propagation modeling is fundamental to the design and planning of wireless communication systems. To date, cellular networks have been primarily deployed in the sub-6 GHz frequency bands. The principle motivation for operating at lower frequencies is better free-space, building and foliage penetration, and lower oxygen-absorption losses, providing extended range. Channel models have evolved in lockstep to support these bands. In the past decade, however, transmission from data-intensive mobile devices has created a "spectrum crunch," prompting the wireless community to investigate mmWave bands (30 – 300 GHz) as an alternative [22-24]. While research continues to improve spectral efficiency in sub-6 GHz bands, the international cellular community is also focused on the 28 GHz and 39 GHz bands, with interest in the 72 GHz and 82 GHz E-Band growing. The IEEE 802.11ay standard focuses on the 60 GHz frequency band. Although propagation is less favorable in the mmWave regime, channels with much wider bandwidths – in excess of 4 GHz with data rates beyond 170 Gigabits/second – are now available.

MmWave wireless systems embody more than a simple shift in the center frequency and represent a significant departure in technology from their predecessors. To extend their inherently limited range due to the additional path loss, phased-array antennas with gains on the order of 30 dBi or higher must be employed at both ends of the link. The short wavelengths relax the constraints on form factor for implementing these massive arrays, involving tens to hundreds of elements, on mobile devices. Since antenna beamwidth is inversely proportional to its gain, the arrays are anticipated to have extremely narrow "pencil beams" of the order of a few degrees. Despite their narrow beamwidth, they can still cover an omnidirectional field-of-view through electronic steering, which is critical for mobile applications. Specifically, the transmitter and receiver will steer their beams along the respective angles-of-departure (AoD) and angles-of-arrival (AoA) of any viable propagation paths between the two. From a channel-modeling perspective, we must determine how many paths are available in an environment, as this value maps to the maximum number of independent data streams that can be sent. Also critical are models for the strength of the paths and their distribution in the AoD-AoA space. Measured data that capture these geometrical properties are, thus, needed to develop meaningful channel models on which component and system development can be based. Simply extrapolating current sub-6 GHz models to mmWave frequencies is not sufficient.

To address these challenges, NIST has developed mobile channel sounders at 28 GHz, 60 GHz, and 83 GHz [25-29] (see Figure 5, (a)-(d)). Although most channel sounders implement virtual arrays (through mechanical translation or rotation of a single element), the total channel sweep may take a long time (often hours), so only static environments can be evaluated. We have employed an alternative design that consists of multi-element, circular arrays at both the transmitter and receiver such that AoD and AoA of the channel propagation paths can be extracted. Figure 5(b) shows our receive array at 60 GHz and the full 60 GHz receive system mounted on a mobile platform is shown in Figure 5(d). Thanks to fast electronic switching, a total channel sweep takes only 262 µs. This means that the properties of dynamic channels can be captured up to a closing speed of 35 km/h [28]. Consequently, we can collect measurements for Doppler spread, whose accurate characterization is essential to determine channel coherence time and for the design of equalization schemes. This will be particularly important for tests at vehicular speeds. The system can quickly record hundreds of channel measurements in a single environment to reliably fit models from many data points. These models rely on environment maps, which our system can generate through its laser-guided navigational system. These so-called "map-based" models are driving the latest mmWave system standards [30-32]. More information on the instrumentation, time synchronization of clocks, array multiplexing, and data processing can be found in [25-29].

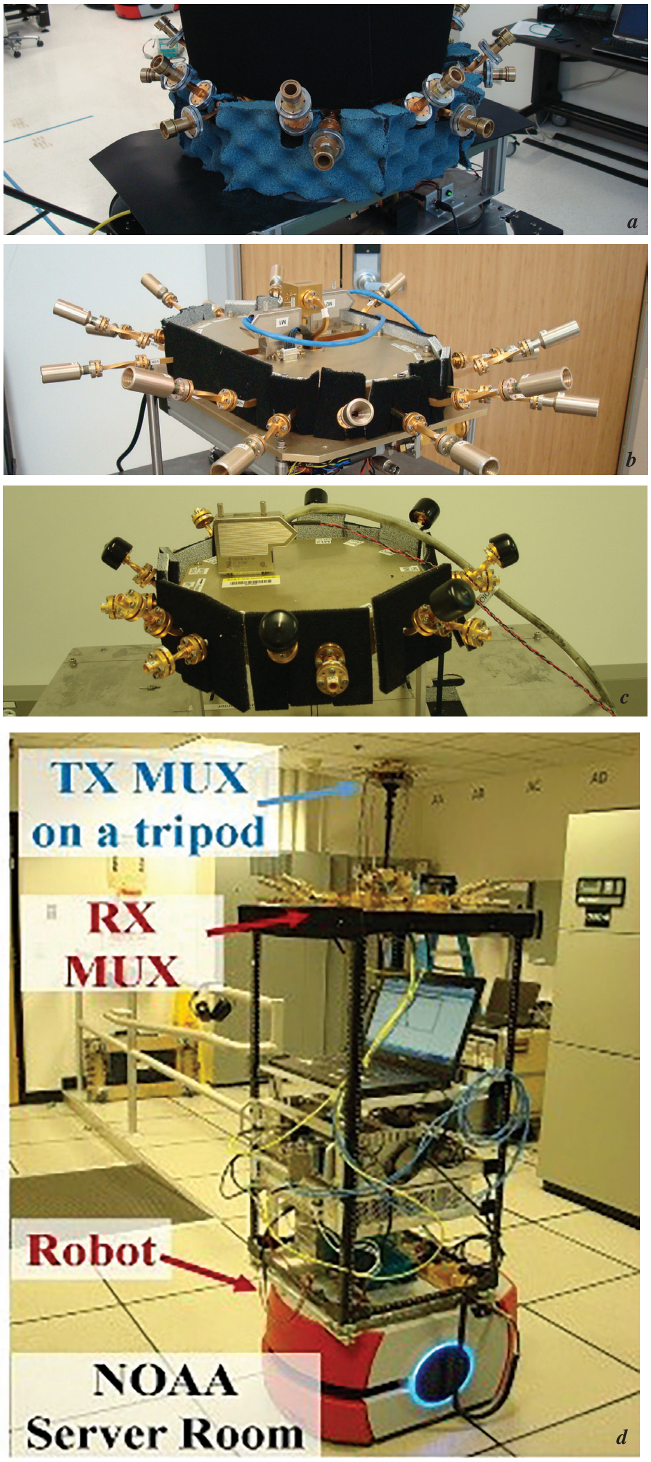

Figure 5:16-element receive arrays for the NIST mmWave channel sounder. (a) 83 GHz; (b) 60 GHz; (c) 28 GHz. The array elements have a beamwidth of 22.5° and a gain of 18.1 dB. Every second element is elevated by 22.5° to give a fat toroidal pattern in the upper hemisphere. (d) The 60 GHz receive array mounted on a mobile platform (robot). The robot can first map a space using the robotic platform's lidar system, assign a coordinate system, and then log location as the robot acquires channel-sounding data on an assigned path.

The challenges of mmWave wireless systems extend beyond the additional path link loss; operation at such high frequencies requires dealing with very short wavelengths. A timing error of just 0.01 ns at 800 MHz, where commercial 4G providers operate today, translates to a phase error of 2.9°. While non-ideal, this still permits coherent beamforming across the elements. The same timing error at 60 GHz translates to a phase error of 216.0°; i.e., no phase coherence. NIST is a leader in quantifying timing errors in mmWave systems. Besides timing errors, we have implemented many calibration methods to improve the dynamic range and system response of our channel sounders.

To better quantify phase error, NIST has implemented a virtual planar phased-array antenna by mounting the receiver on a two-dimensional positioner that sequentially displaces an array element through mechanical scanning. A photo of this system is shown in Figure 6. The virtual antenna will serve as a testbed to gauge how timing error translates into phase error and ultimately into angular estimation error in our channel sounders. The testbed will also enable us to measure spherical wave fronts and design methods to calibrate them. A looming question in the wireless community is: How big are the differences in propagation characteristics across the mmWave band? For example, the wavelength difference between the frequencies of 60 GHz and 83 GHz, translates to a change of just 1.4 mm in wavelength. Lacking precision equipment, any minute change in propagation characteristics will go unnoticed. Our virtual testbed will permit answering these questions for a wide range of environments with different ambient structure materials. Finally, we are investigating the use of state-of-the-art phased-array antennas for channel sounding at 60 GHz (Figure 7).

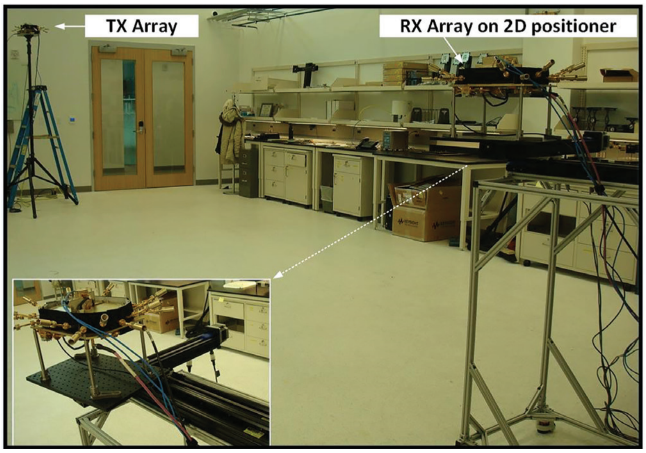

Figure 6: Virtual planar phased-array antenna. The 2D positioner moves across 30 x 30 positions spaced a half-wavelength apart (5 mm at 60 GHz), the same spacing between elements in a phased-array antenna.

Further communications and interference questions that need to be answered are: provided channel-state information, how many independent streams of data can be sent along the multipath directions while avoiding interference between the associated beams? Given a fixed number of phased-array elements, how does one determine how to partition the elements? Or, rather than generating multiple beams, is it more beneficial to allocate elements to create nulls along the directions of potential interferers, increasing the signal-to-noise ratio?

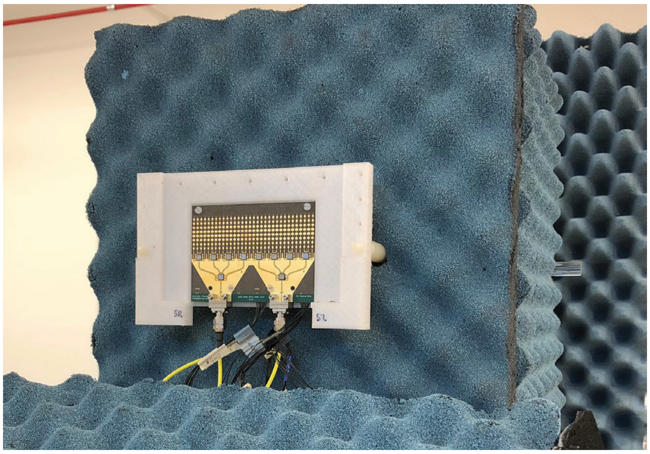

Figure 7: 60 GHz phased array antenna to be used with NIST channel sounders.

Antenna Metrology for Smart Antennas and MIMO Systems

MIMO systems provide a path to further increase user density beyond current in-band mulitiplexing protocols such as CDMA and TDMA. Thus, industry is looking toward the use of larger-scale MIMO, dubbed "massive MIMO," to increase capacity. The use of more advanced antenna technologies, such as adaptive/multiple-element-array systems [33-35], shows promise for realizing massive MIMO. Dynamic antenna technologies such as beam-forming arrays can also capitalize on both spectral and spatial diversity. These would allow for high-performance base stations and, ultimately, user equipment that have multiple static or steering beams to realize much smaller, and possibly moving sectors. Future MIMO systems will optimize spatial diversity through beam control and null space steering or reconfiguration.

To increase system throughput and reduce fabrication costs, high levels of integration will be used for massive MIMO antenna technology. Antenna architecture may vary widely from printed circuit boards to highly integrated CMOS structures. Much like today's cell phone antennas, which are bonded right to the printed circuit board along with other electronic subsystems, massive MIMO arrays will need to be tested with over-the-air techniques. Industry groups such as 3GPP and CTIA have worked hard to develop OTA test procedures for two-element MIMO systems; however, the currently proposed techniques are not scalable in frequency. Increasing the complexity of such tests to a much larger number of elements is a key barrier to development of advanced cellular systems.

One challenge is to identify gaps in current antenna array measurement techniques and establish methods that will align with the requirements for advanced communications systems. As an initial step, NIST is establishing a testbed that gives full control over the entire antenna system including the location of array elements, individual element RF control, and local oscillator distribution. We are building a 70-75 GHz scalable MIMO system consisting of a 4-element antenna array communicating with two separate external antenna elements.

This testbed will be used to establish OTA methods for highly integrated MIMO systems at mmWave frequencies. We seek to develop methods to characterize element-to-element drift and imbalance criteria at a stand-off distance from the antenna system. These measurements will help to inform industry practitioners about what subset of the mmWave MIMO parameter space they should focus on. This will also allow element-by-element characterization of antenna arrays without requiring full time-intensive near-field scans and provide knowledge needed for development of test methods.

In parallel, NIST is creating a new state-of-the-art antenna measurement facility (AMF). The AMF starts with a fully anechoic shielded chamber (15.5 m x 7.3 m x 6.7 m) that provides a radio quiet environment for antenna metrology. Two antenna positioning systems will then be installed that together will cover the 1 GHz to 500 GHz frequency range. The first is a newly conceived large antenna positioning system (LAPS) [36], depicted in Figure 8, that will cover the 1-50 GHz frequency range. The LAPS consists of two six-degree-of-freedom articulated arm robots, one fixed and one on an 8 m long floor-mounted rail. The LAPS can track and measure multiple beams from electrically steered array antennas, simulate Doppler effects using dynamic antenna positioning, and scan entire systems consisting of multiple antennas with improved accuracy and repeatability. A phase-coherent receiver system is being developed that will be used to acquire the OTA RF measurements on the LAPS. In addition to the LAPS, a second high-frequency robotic antenna range covers mmWave frequencies from 50 GHz to 500 GHz [37]. They will be used for the development of the high-frequency OTA test methods.

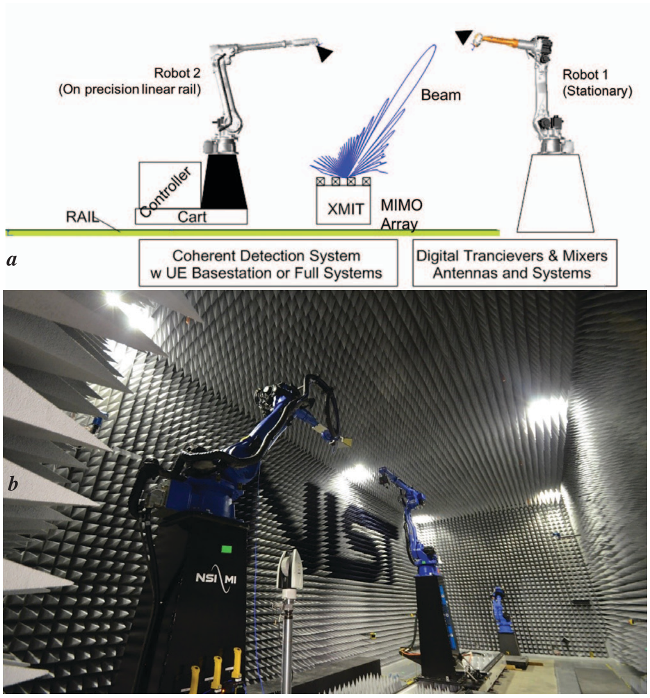

Figure 8: The NIST Large Antenna Positioning System (LAPS): (a) the concept and (b) a photo of the installed system.

Shared Spectrum Metrology

The spectrum crunch is highlighting the reality that spectrum is both a valuable and limited resource. The push toward IoT will only increase the pressures on this limited resource, and the physics of RF propagation ensure that frequencies below 10 GHz will remain a part of the solution. Going forward, spectrum will need to be used more optimally and shared among a growing number of users. Thus, there exist EMC challenges related to both coexistence, where multiple users share the same spectrum, and to dynamic spectrum allocation, where spectrum is allocated in real time among a prioritized set of users.

As noted, when multiple wireless technologies coexist in the same or adjacent frequency spectrum, they can generate mutual interference with the potential to alter their behavior and performance. Coexistence test methods need to be developed to standardize the process by which these effects are evaluated in uncoordinated industrial, scientific, medical (ISM) bands (e.g., the popular 2.4 GHz). These unlicensed bands may serve as a model for future spectrum re-allocation as they allow for flexible and cost-effective product development. However, a key question is whether coexistence can be maintained as the density of devices increases in ISM bands. Building on the recent IEEE/ANSI C63.27 standard that focused on a limited number of communication links, further EMC test methods to address this aggregation question are needed. Uncertainty analysis that considers the EMC impacts due to information-layer transactions is an open area of research.

There is also a growing need to develop improved in-situ noise floor and RF interference metrology. The proliferation of wireless devices has profoundly changed the nature of ambient RF conditions, and understanding the magnitude and impact of this change is critical for devices that rely on signals close to or below the noise floor (e.g., GPS/GNSS). Work is needed to characterize modern RF conditions beyond the current simple noise models (e.g., Gaussian white noise). Replicating the multitude of noise, multipath, and aggregate environments with sufficient accuracy such that reliable tests can be designed will be a difficult challenge.

Coexistence test methods can serve as a first step toward evaluating coordinated sharing in licensed bands like the proposed 3.5 GHz citizens broadband radio service (CBRS). Once spectrum coordination solutions become available for testing, EMC metrology research can expand to other areas like priority-user interference protection or system spectrum utilization efficiency. Theoretical models grounded in measurement data are needed to address the statistical nature of interference and coexistence.

An emerging tool for spectrum and interference measurements is unmanned aerial systems (UAS). UAS are already deployed in a variety of RF applications: in RF measurements as a means to characterize large antenna arrays typical of radio astronomy infrastructure [38-40], in environmental monitoring as a spectrum monitoring [41] and mmWave imaging [42] tool, and in communications as a backhaul platform for disaster relief [43-44]. UAS have a great potential to become permanent elements of communications infrastructure and RF field testing [45-49]. Industry is developing various implementations of communication backhaul systems using high-altitude UASs [50-51] and low/medium orbit satellites [52-53] that may have to coexist or share spectrum with existing terrestrial and geostationary networks. This presents new questions in EMC metrology with regards to direct, adjacent-band, and aggregated interference effects between the different dimensional (terrestrial, high altitude, earth orbit, and geostationary) communications assets.

Furthermore, as UAS systems (small- or large-scale) are being deployed in RF measurement campaigns there is a need to ascertain the uncertainty, reliability, and sensitivity of such systems. Particularly so, where UASs could be deployed in adjudication scenarios; e.g., real-time spectrum monitoring, dynamic spectrum allocation sensors, or as probes for testing out RF infrastructure. With the proliferation of UAS technology, there are challenges to refine and redefine RF metrology and spectrum sharing techniques to better understand EMC issues, particularly in the face of growing aggregate interference.

Measurement Uncertainties

Measurements are made more meaningful once uncertainties are assigned, as is increasingly recognized in EMC standards. Complex systems, or correlations between time and frequency domain data are difficult to handle analytically. Thus, software approaches are needed. The NIST MUF [54] is a tool that allows us to assign uncertainties and probability distributions to error mechanisms in microwave and mmWave calibrations [55]. It propagates the associated uncertainties through the calibration process to the end result while maintaining correlations both between frequencies and calibration standards used in different parts of the process. The framework captures correlations in the uncertainties by assigning a name to each error mechanism and representing the resulting errors as perturbed measurement vectors that are propagated from one calculation step to the next. This allows uncertainties throughout the calculations to be correctly correlated even when the same uncertainty mechanism is introduced at different stages of the calculation, such as when VNA calibration artifacts are used for different aspects of mismatch corrections.

The MUF simultaneously performs both a sensitivity analysis and a Monte-Carlo analysis. The sensitivity analysis is based on an assumption that the errors are Gaussian and the problem is linear. The Monte-Carlo analysis is run concurrently with the sensitivity analysis. It can be used to check the assumptions of the sensitivity analysis, propagate uncertainties through highly nonlinear problems, estimate non-Gaussian probability distributions, and detect statistical bias in the results. As with the sensitivity analysis, the Monte-Carlo simulator uses the name of each error mechanism to maintain correlations.

Uncertainties provided by the MUF may readily be applied to VNA measurements [3-5]. However, the MUF also provides the relatively straightforward propagation of uncertainty to the measurement of other quantities such as radiated power [56] and antenna efficiency [57], and even derived parameters such as EVM [3] and the power delay profile.

Conclusion

Future "5G and beyond" wireless systems will present new and challenging EMC problems. Fundamental microwave and field metrology will be needed to develop accurate and meaningful EMC test methods and standards. This paper has presented some ideas on the metrology needs and the NIST plans to address them. But so much that will define the interference landscape in the years ahead is hard to anticipate. We shall see where advanced communications and the IoT lead the EMC community, particularly in the broad area of wireless systems considered here.

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Biographies

Perry F. Wilson *(S'78-M'82-SM'93-F'05) received his Ph.D. in Electrical Engineering from the University of Colorado in 1983. He led the RF Fields Group in the RF Technology Division of the National Institute for Standards and Technology, in Boulder, Colorado until recently retiring. Dr. Wilson's research has focused on the application of electromagnetic theory to problems in electromagnetic compatibility and RF field metrology. Dr. Wilson is a Fellow of the IEEE, a member of US IEC TC77B TAG, past Editor-in-Chief of the IEEE EMC Transactions, a recipient of a 2010 IEEE EMC Society Technical Achievement Award, a recipient of the 2002 IEEE EMC Transactions Best Paper Award, and a recipient of a 2007 US Department of Commerce Gold Medal.*

Kate A. Remley *(S'92-M'99-SM'06-F'13) was born in Ann Arbor, MI. She received the Ph.D. degree in Electrical and Computer Engineering from Oregon State University, Corvallis, in 1999. From 1983 to 1992, she was a Broadcast Engineer in Eugene, OR, serving as Chief Engineer of an AM/FM broadcast station from 1989-1991. In 1999, she joined the RF Technology Division of the National Institute of Standards and Technology (NIST), Boulder, CO, as an Electronics Engineer. She is currently the leader of the Metrology for Wireless Systems Group at NIST, where her research activities include development of calibrated measurements for microwave and millimeter-wave wireless systems,* characterizing the link between nonlinear circuits and system performance, and developing standardized test methods for the wireless industry. Dr. Remley was the recipient of the Department of Commerce Bronze and Silver Medals, an ARFTG Best Paper Award, and is a member of the Oregon State University Academy of Distinguished Engineers. She was the Chair of the MTT-11 Technical Committee on Microwave Measurements from 2008 - 2010 and the Editor-in-Chief of IEEE Microwave Magazine from 2009 - 2011, and is the Chair of the MTT Fellow Evaluating Committee. She is a past Distinguished Lecturer for the IEEE Electromagnetic Compatibility Society (2016 - 2017).

Dr. William Young received a MS from Washington State University, Pullman in 1998 and a PhD from the University of Colorado, Boulder in 2006, both in electrical engineering. At Sandia National Laboratories, between 1998 and 2003, his contributions included design, validation testing, information security assessment, and accreditation of communication systems for the DoD, the Defence Science Organisation in Singapore, and the Bureau of Reclamation. Selected for the Sandia Doctoral Studies Program in 2003, his research focused on optimizing RF propagation from ad hoc wireless arrays and characterizing RF penetration of large buildings. From 2006 to 2010 at Sandia, he investigated electromagnetic interference on wireless LANs applied to spaceborne telemetry applications, and the use of MIMO for perimeter intrusion detection. From 2010 to 2018 at NIST, Dr. Young developed radiated test methods for evaluating the RF performance of wireless communication devices, including the application of electromagnetic reverberation chambers and real-world RF environment statistics for the National Fire Protection Association Electronic Safety Equipment Committee. He was a key technical contributor to the NFPA 1982: Standard for RF Personal Alert Safety Systems, and the ANSI C63.27 - Standard for Evaluation of Wireless Coexistence, published in May, 2017. From 2016 to 2018, he served as the Group Leader for Shared Spectrum Metrology in the NIST Communications Technology Laboratory, and the technical lead for the National Advanced Spectrum and Communication Test Network investigation of LTE impacts on GPS L1 Band receivers. In 2018, Dr. Young joined the MITRE Corporation, where he currently serves as a subject matter expert in test and evaluation of spectrum sharing technologies. He also teaches classes on radio frequency measurements at the University of Colorado, Denver.

Camillo Gentile (M'01) received the B.S. and M.S. degrees from Drexel University in 1996 and the Ph.D. degree from Penn State University in 2001, all in electrical engineering. He joined the National Institute of Standards and Technology in 2001. He has authored over 60 peer-reviewed papers and a book on geolocation techniques. In 2015, he became a project lead. His current interests include channel modeling and physical-layer modeling for millimeter-wave communication systems.

John Ladbury received the B.S.E.E. and M.S.E.E. degrees (specializing in signal processing) from the University of Colorado, Boulder, in 1987 and 1992, respectively. Since 1987 he has worked on EMC metrology and facilities with the Radio Frequency Technology Division of N.I.S.T. in Boulder, CO. His principal focus has been on reverberation chambers, with some investigations into other EMC-related topics such as time-domain measurements and probe calibrations. He was involved with the revision of RTCA DO160D and is a member of the IEC joint task force on reverberation chambers. He has been awarded four "Best Symposium Paper" awards at IEEE International EMC symposia, a Technical Achievement Award from the IEEE EMC Society for significant contributions in the development of reverberation chamber techniques for EMC applications, a US Department of Commerce Bronze Medal for his research in Reverberation Chambers, and a US Department of Commerce Gold Medal for helping to develop tests to assess the impact of LTE wireless signals on the performance of GPS receivers.

Dylan F. Williams received a Ph.D. in Electrical Engineering from the University of California, Berkeley in 1986. He joined the Electromagnetic Fields Division of the National Institute of Standards and Technology in 1989 where he develops electrical waveform and microwave metrology. He has published over 100 technical papers, is a Fellow of the IEEE and is the recipient of the 2013 IEEE Joseph F. Keithley Award. He served as Editor of the IEEE Transactions on Microwave Theory and Techniques and as 2017 President of the IEEE Microwave Theory and Techniques Society.

The 2018 IEEE EMC+SIPI Symposium in Long Beach, California offered many educational opportunities to attendees, including oral and poster papers (top) as well as an outstanding keynote address by Prof. Yahya Rahmat-Samii of UCLA (bottom) and a series of hands on demonstrations and experiments (see page 46).

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