Implementation of a Novel, Sparse, Irregular, Multi-Probe Array System for the Rapid Production Test of 5G Massive MIMO Antennas

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Abstract—**As the seemingly never-ending desire for ever more data continues, so too does the need for ever more complex antennas operating at ever higher frequencies which are required to satisfy this insatiable demand. This, of course, places greater demands on the associated measurement system with ever increasing acquisition times. Previously, measurement engineers have had the luxury of being able to exhaustively measure these devices, relying upon rigorous but arguably expensive sampling theorems. Unfortunately, in recent years such approaches have become unaffordable. Compressive Sensing (CS) and Sparse Sampling techniques have been applied in a variety of free-field metrology-based applications in an attempt to rein in the amount of data samples required without sacrificing resolution. Recent studies have shown that CS can potentially be used to drastically reduce the number of measurements required to verify antenna array excitations in a demanding time critical production test environment. The process involves a near-field measurement comparison of the test article to that of a 'gold' reference antenna under identical test conditions utilizing a total variation strategy. However, this process is sensitive to non-repeatable measurement errors, for example due to mechanical position and RF thermal drift. To combat these errors, a test fixture comprised of an array of fixed RF probes is proposed to rapidly and sparsely sample the nearfield of both a 'gold' reference and ensuing test articles for the purpose of very quickly identifying array failures in a production facility**.

Keywords—Array Diagnostics, Production Antenna Test, Massive MIMO, Planar Near-field, Compressed Sensing, Sparse Sampling.

I. INTRODUCTION

With the growing demand to produce larger, more complex active phased array antennas comes the need to cost effectively test and calibrate them in a production environment. Traditionally, near-field measurement techniques have been used for phased array antenna calibration, validation, and fault detection. These techniques involve measuring the electric field close to the array aperture and then employing a mathematical algorithm to transform the near-field data to the radiated far-field response or use microwave holographic metrology to verify element excitations. Since the electrical size of the aperture dictates the required near-field sampling rate, measurement times for electrically large arrays can be significant. An alternative approach is to use a "Park & Probe" method, where the near-field RF probe is used to measure the frequency responses of individual array elements [1]. This too can be quite a time-consuming process for large numbers of elements, many control states and across a band of frequencies. Hence the need for alternative methods to reduce validation process times.

In a production environment, it is feasible to assume the existence of a 'gold' reference antenna: i.e. one that has been developed to meet specification and is to be replicated in mass production. The known measurement response of this same reference antenna could potentially be used for "quick and dirty" antenna verification tests. For example, comparing one-dimensional cuts, or by taking drastically under sampled near-field measurements to determine a pass or fail condition. However, there is still the desire to also detect and identify faulty elements in a timely manner so that they can be readily remedied. Recent developmental efforts using Compressed Sensing (CS) have investigated how this powerful digital signal processing technique can be leveraged to reduce planar near-field measurement times without scarifying the sensitivity needed to identify faulty phased array elements. It has been previously demonstrated that CS, using the equivalent currents method, can be successfully used to identify faulty elements for arrays with up to 4% failure rates [2] using only 1.5% of the samples needed by a conventionally sampled near-field plane. The overall procedure of CS based defective array detection is illustrated in Fig. 1. A comprehensive discussion of the CS principle is beyond the scope of this paper, however more information is available in the open literature, *e.g.* [5].

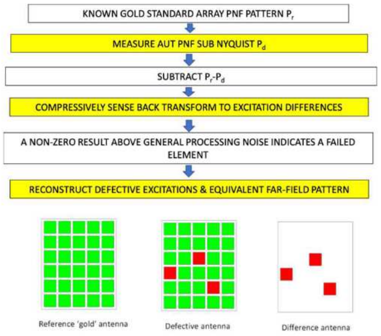


Fig. 1. Top: Flow diagram of defective element detection using compressive sensing. Bottom: the 'sparse' difference antenna concept.

II. COMPRESSIVE SENSING METHOD

Compressive Sensing (CS) and Sparse Sampling techniques have been deployed in a variety of free-field metrology-based applications including radar imaging [6], cylindrical [7] and spherical near-field measurements [8, 9], far-field reflection suppression [10], and for array antenna measurement and diagnostics [11, 12, 13, 14]. Compressed (or compressive) sensing is a signal processing technique developed in the field of applied mathematics that can be used for efficiently acquiring and reconstructing a signal by finding solutions to underdetermined linear systems. The basis of this technique relies on exploiting the sparsity of a signal to recover it from far fewer samples than required by the Nyquist-Shannon sampling theorem. There are two conditions under which recovery is possible: the first one requires the signal to be sparse in some domain, and the second one is measurement incoherence. Compressive sensing has traditionally been used in imaging applications, MRI for example. In recent years, there has been much developmental work exploring how this powerful processing technique can be leveraged for other applications such as antenna characterization. Latest efforts have largely focused on the use of compressed sensing to reduce the number of measurement samples, and hence also reduce excessive measurement times, which are often encountered in planar near-field antenna measurements.

One of the basic principles behind compressed sensing is the determination of a sparse and sporadic data set that adequately recovers the desired signal. In the case of antenna near-field measurements, this translates to randomly collected data samples within the near-field measurement extent. The keyword in this statement is *random*. Compressed sensing can be used to determine an optimized random data set that when transformed to the far-field, provides an acceptably accurate representation of the antenna's far-field radiated field. In massive MIMO array characterization, CS has been successfully used to drastically reduce the number of measurements required to verify the antenna array's excitation in a production test environment [2, 3] assuming failure rates of less than *circa* 5%. Failure rates that are higher than this level are still manageable, but the accuracy of the reconstructed elemental excitation is reduced. However, faulty elements are still correctly flagged.

III. IMPLEMENTATION CONSDIERATIONS

Traditional near-field antenna measurement solutions generally employ mechanical positioning systems that are designed to collect measurement samples over a uniform sampling grid at a constant rate of motion, making measurements at random positions inconvenient. While the benefits of this technique are well understood, the actual implementation has been difficult due to the limitations of these systems. One possible solution is to use an industrial, multi-axis robotic arm [4]. Designed to be efficient, reliable, and extremely repeatable, robotic arms provide the flexibility to measure a variety of antenna topologies using non-uniform sampling intervals if desired. This tool provides the antenna measurement community with the capability to randomly sample a measurement surface for compressed sensing applications.

Previous analysis has shown that the CS solution is highly sensitive to z-translational positioning errors and requires mechanical position repeatability of the probe to the AUT within 0.002λ [15]. While a robotic arm can easily satisfy this criterion at frequencies < 6 GHz, it becomes increasingly more difficult to achieve at higher frequencies. And, even if we were able to design a mechanical system that could achieve accuracies that were within the 0.002λ (0.7^{o}) criteria, such a phase error could also have been generated by cable fluctuations or RF thermal drift.

An alternative approach is to use a sparsely populated planar array of low cost probes connected via a PIN switch matrix to a Vector Network Analyzer, a sort of sparse, compact, near-field multi-probe anechoic chamber (NF-MPAC). In addition to being a more cost effective solution than a robotic arm, it facilitates an extremely rapid measurement process and thus mitigates phase errors due to RF thermal drift and cable movement.

This array test fixture will be positioned in the nearfield of our antenna under test (AUT) using a mechanical reference mounting interface to facilitate repeatable mechanical alignment of our array test fixture with respect to the AUT. Again, we are interested in the difference measurement between our AUT and 'gold' reference antenna under assumed identical conditions. Concern is only of non-repeatable errors introduced between these two measurements as repeatable factors are compensated by the differential nature of the total-variation measurement methodology.

IV. TEST SYSTEM IMPLEMENTATION

For this investigation, the goal was to implement a *rapid* and cost effective production test system for a 5G Massive MIMO array with the capability of detecting individual element failures. The production antenna was an 8x24 (192 element) MIMO array with $0.5\lambda \times 0.7\lambda$ element spacing, operating at frequencies from 3.4 to 3.6 GHz (*cf.* Fig. 2).

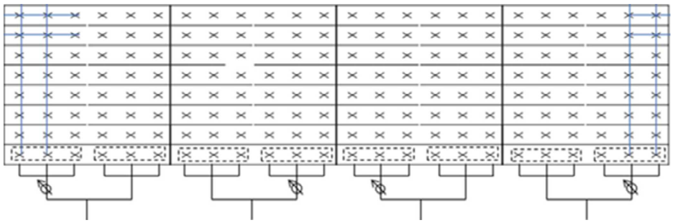


Fig. 2. Massive MIMO production array architecture

In a previous study, we investigated the number of randomly located NF samples required to achieve reasonable CS reconstruction accuracies and discovered just 25 samples were all that was needed to detect up to 2% radiating element failures in the 8x24 element MIMO array, which is the expected production mortality rate [2]. Fig. 3 summarizes the expected NF CS RMS amplitude reconstruction error for different element fault levels, and from this we determined the number of samples required to achieve our 2% detection target (4 faults in this case) using a reasonable -25dB RMS reconstruction error limit.

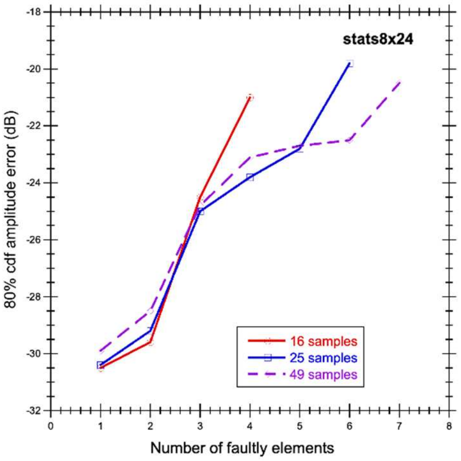


Fig. 3. 80% CDF RMS amplitude reconstruction error vs number of faults for the 8x24 array for different numbers of NF samples.

To satisfy the CS algorithm sampling criteria, the probes will be pseudo-randomly positioned within the planar array extent, the locations pre-selected and optimised by stochastic simulation to provide the optimum algorithm performance based on simulation results for this particular Massive MIMO antenna [2].

A. Beamforming Network

The beamforming network of our 25-element test array is comprised of an RF switching network consisting of four 8-port PIN switches and one 4-port PIN switch connected by semi-rigid coaxial cable to a VNA as shown in Fig. 4. Test System Block Diagram Switch settings will be automatically controlled through the measurement acquisition software via a high-speed PIN switch controller. Switching speeds are on the order of 1 µs, resulting in a total acquisition time of < 1 s for all 25 probes at a single frequency.

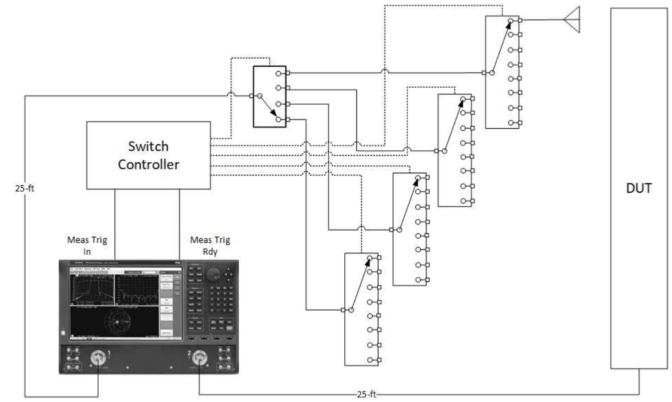


Fig. 4. Test System Block Diagram

While there is a conscientious effort to adjust RF cable lengths to provide equal RF electrical paths to all elements, slight variances are not of major consequence as these are expected not to change between antenna measurements and will subsequentially cancel out within the near-field data subtraction process.

B. Element Antenna

The proposed probe for our validation array is a co-planar Vivaldi notch (*cf.* Fig. 5Fig. 5), selected for its broadband characteristics, low scattering cross-section, and simple yet scalable design, making it a very cost-effective antenna to manufacture for frequencies of *circa* 1 GHz and higher.

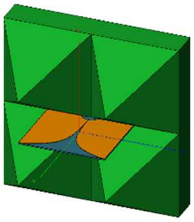


Fig. 5. Vivaldi Probe

The Vivaldi notch demonstrates low scattering characteristics by nature due to its narrow profile, and absence of need for a ground-plane making it a popular radiating element antenna for many applications including within active electronically scanned array antennas. It also has promises to have less interaction with the AUT than an OEWG probe. While it is possible to manufacture a dual-pol Vivaldi antenna, a single-pol probe will be used for this application as it provides the absolute minimum scattering cross-section. The error uncertainty due to multi-reflections between the probe and AUT can be assessed by varying the AUT-to-probe separation distance by ¼ λ between two back-to-back PNF measurements and comparing the resulting far-field patterns [18]. Simulations were performed to determine the potential multi-reflection error for our proposed probe and AUT, resulting in an RMS dB difference level of -55.17 dB as shown in Fig. 6. This error level corresponds to an uncertainty of less than ±0.02 dB.

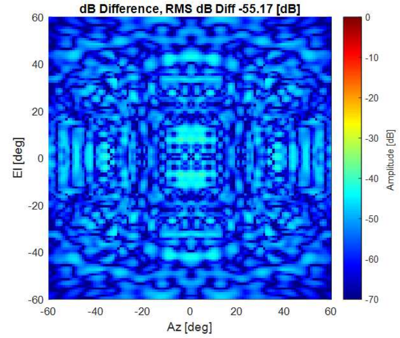


Fig. 6. Simulated far-field difference pattern showing predicted multi-reflections between AUT and probe.

Varying multi-reflection interactions between our probe and test article are of concern as a potential failed element could affect the nature of the scattering and introduce an additional error into our difference measurement. However, our simulation predicts this error contribution to be really quite small, and as we are only trying to identify failed elements and not exact element excitation values, such an insignificant error term can be tolerated by our CS processing algorithm.

The Vivaldi probe also demonstrates a wide bandwidth, often spanning more than a waveguide band. While our AUT only has an operating frequency band of 3.4 to 3.6 GHz, we wanted to make sure that our probe was well matched at these frequencies. The optimized probe design predicts a VSWR below 1.2 between 3.21 to 3.64 GHz as shown in Fig. 7 below.

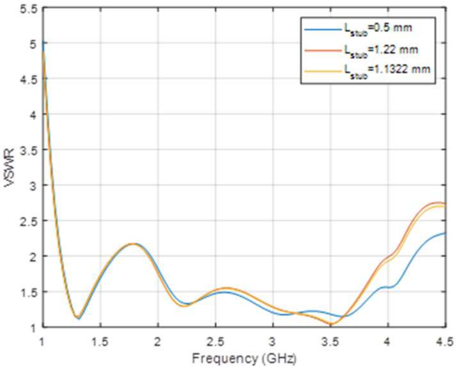


Fig. 7. Vivaldi probe broadband performance

Finally, we ran far-field pattern simulations of our probe over the frequency range 2.0 to 4.0 GHz. The resulting E- and H-plane polar plots can be seen presented in Fig. 8 which show the Vivaldi probe performs well offering a broad-beam pattern that is stable across a broad-band of frequencies.

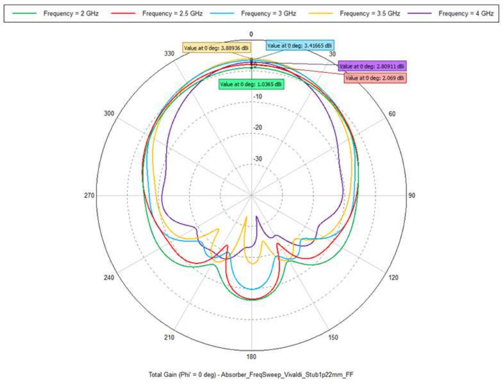


Fig. 8. Vivaldi probe E-plane far-field pattern

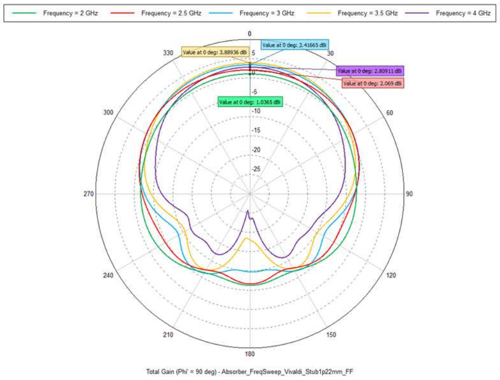


Fig. 9. Vivaldi probe H-plane far-field pattern

C. Mechanical Alignment

Another consideration is the mechanical alignment of the array test fixture with our 'gold' reference and antenna under test. As previously mentioned, the CS algorithm to be used in this application is highly sensitive to varying probe to AUT *z*-distances between our two measurements, requiring mechanical alignment repeatability to be < 0.002λ (0.17mm at 3.5 GHz). There are various metrology techniques, both optical and mechanical, that can be employed to accurately align our 25-element array with the AUT. However, as this is intended for use in a production environment where the emphasis is on speed and ease of use, a mechanical alignment fixture will be used to mount our sparse array directly to the AUT at the desired near-field measurement distance (*cf.* Fig. 9). This mechanical alignment fixture uses locating pins to align with mechanical reference targets on the AUT mechanical fixture. Once aligned with this fiducial reference, the fixture will be securely attached using quick snap locking mechanisms.

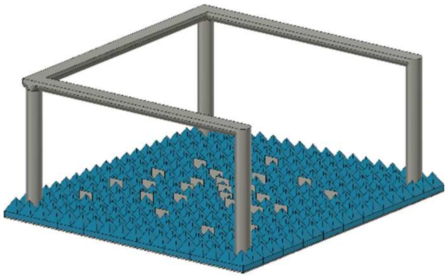


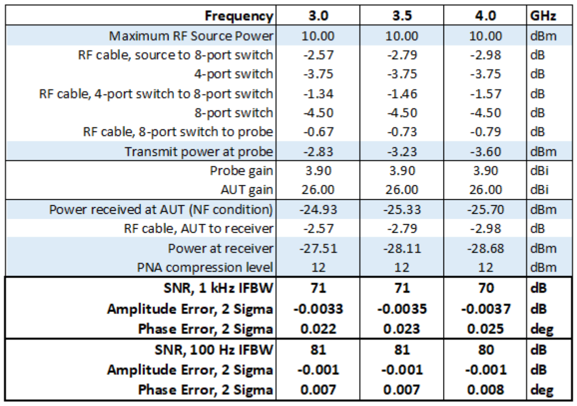
Fig. 10. Mechanical alignment concept

Note that since there is no mechanical movement during the measurement process, the orientation of the AUT and array test fixture are irrelevant. The production antenna can be oriented such that it can be easily accessed, and the array test fixture positioned quickly, with this repetitive task perhaps being performed by an industrial multi-axis robot.

D. *Test System Configuration*

For this concept, a 2-port Keysight N5222B Vector Network Analyzer is used to perform an S21 measurement of our test system configuration. Initial RF link budget calculations (Table 1) estimate a dynamic range > 70 dB using a 1kHz IF bandwidth, (IFBW) which provides a phase uncertainty that is deemed acceptable for our measurement application. If further accuracy is deemed necessary, the VNA IFBW could be further reduced without a noticeable difference in measurement speed. However, even at a 100 Hz IFBW, it is anticipated that the measurement process using our 25-element array will take less than 10 seconds to perform. The ensuing CS algorithm post-processing time for detecting element failures is an additional 10 seconds, resulting in complete antenna validation in under 30 seconds.

TABLE 1. Near-field RF Link Budget Estimate



Frequency	**3.0**	**3.5**	**4.0**	**GHz**
Maximum RF Source Power	10.00	10.00	10.00	dBm
RF cable, source to 8-port switch	-2.57	-2.79	-2.98	dB
4-port switch	-3.75	-3.75	-3.75	dB
RF cable, 4-port switch to 8-port switch	-1.34	-1.46	-1.57	dB
8-port switch	-4.50	-4.50	-4.50	dB
RF cable, 8-port switch to probe	-0.67	-0.73	-0.79	dB
Transmit power at probe	-2.83	-3.23	-3.60	dBm
Probe gain	3.90	3.90	3.90	dBi
AUT gain	26.00	26.00	26.00	dBi
Power received at AUT (NF condition)	-24.93	-25.33	-25.70	dBm
RF cable, AUT to receiver	-2.57	-2.79	-2.98	dB
Power at receiver	-27.51	-28.11	-28.68	dBm
PNA compression level	12	12	12	dBm
SNR, 1 kHz IFBW	**71**	**71**	**70**	**dB**
Amplitude Error, 2 Sigma	**-0.0033**	**-0.0035**	**-0.0037**	**dB**
Phase Error, 2 Sigma	**0.022**	**0.023**	**0.025**	**deg**
SNR, 100 Hz IFBW	**81**	**81**	**80**	**dB**
Amplitude Error, 2 Sigma	**-0.001**	**-0.001**	**-0.001**	**dB**
Phase Error, 2 Sigma	**0.007**	**0.007**	**0.008**	**deg**

V. CONCLUSION

Presented is an implementation of a sparse, irregular, multi-probe array test fixture for facilitating the use of compressive sensing to rapidly identify Massive MIMO array failed elements in a production environment. Our high-speed test array comprised 25 quasi-randomly placed fixed near-field Vivaldi probes connected via a PIN switch matrix to a Vector Network Analyser (VNA), where we may run the VNA at a narrow 10Hz bandwidth to maximize the noise suppression. Assuming the entire RF measurement takes *circa* 10 seconds, a very conservative estimation that is in part predicated upon the switching and settling time of the massive MIMO antenna, the whole production test could take less than 30 seconds. For previously tested and corrected antennas, re-testing (this time with fewer faults and hence more sparsity) will provide even more accurate determination of any remaining faults. With such short test times, several rounds of correction and re-test become easily viable.

It is important to emphasise that because the CS process is based on the difference between a “gold” and AUT nearfield, the actual excitation used for the array elements is not important, so any excitation in amplitude and phase can be used. Thus, a practical implementation of the proposed system may well employ a number of different beam directions and shapes.

Comparing this proposed system to conventional planar near-field measurement at Nyquist sampling and subsequent back projection to the array aperture would require 1,537 near-field samples. This is based on a near-field sampling region size of 26.5λ×14.5λ, which would provide far-field azimuth and elevation patterns valid out to 60° [16]. Our proposed method, requiring just 25 samples, represent 1.6% of the amount required by the classical Nyquist sampling and conventional aperture diagnostics [17].

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