Electromagnetic Testing and Failure Prediction of Antenna Systems Using Intelligent Technologies

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Abstract— **This paper provides an analysis of the core technologies in modern wireless telecommunications, which necessitates a transformation of electromagnetic testing and diagnostic methodologies for radio-frequency components. Particular attention is given to post-production OTA methods that enable non-invasive assessment of active antenna systems under realistic operating conditions. The integration of intelligent algorithms, including machine learning and deep neural networks, is discussed as a means of enhancing defect detection efficiency and developing predictive models of failures based on the analysis of large-scale measurement data.**

Keywords—electromagnetic testing; defect detection; machine learning; neural networks

I. Introduction

Active antenna systems are increasingly important part of contemporary telecommunication networks ensuring high speed data transfer and reliability. While the development of new standards comes with growing data traffic and more stringent performance requirements, both lead to a more complex antenna array architecture [1]. In particular, the 5G networks use mmWave massive MIMO arrays containing hundreds of elements [2], which raises serious questions about measurement and diagnostics abilities.

Increasing count of ports and the miniaturization of DUTs make classic conductive testing schemes non-feasible [3], thus underlining importance to OTA measurement principles which give complete system analysis without physical connections [4], [5]. Another potentially beneficial line of research lies in the inclusion of intelligent technologies: machine learning and deep neural networks [6], [7] that enhance the accuracy for defect detection and provide predictive failure modeling capabilities [8].

II. Key technologies of the fifth Generation

The latest generation of wireless communication technology is standardized as 5G New Radio (NR) globally since 2018 [1]. It makes use of the millimeter-wave (mmWave) bands, particularly those within 24–40 GHz, in combination with massive MIMO techniques, enabling a significantly increased network capacity and a large coverage area [2].

Millimeter-wave (mmWave) is one of the key enabling technologies for 5G, providing enhanced peak data rates, ultra-low latency and massive connections to support self-driving cars and telemedicine applications [2]. But mmWave signals experience severe path loss and beamforming is used to focus energy and limit interference [4]. Side by side, the large MIMO arrays increase spectral efficiency and present a formidable research challenge on testing. Scaling down and large-range number of elements render conductive methods not suitable, driving towards non-intrusive OTA techniques for full characterization [9], [5].

In conclusion, though the 5G related technologies make advanced applications available more than ever before, they significantly raise the requirement of testing and diagnostic infrastructures, making OTA techniques merging with smart technology imperative for their reliable operation.

III. Classification of Testing and Fault Detection Methods

Quality of service measurement tools in next generation networks - advance testing/diagnostic infrastructure for active antenna systems A multitude of different methods are used during production to check for potential sources of error prior to commissioning. Strict control with the lowest defective appearance on each spare part, we can assure you that our quality is not only equal to but also exceeds others. Recent technological developments also allow for more automation and provide diagnostic improvements, which is especially necessary when complex designs like massive MIMO are considered [2].

Testing techniques are commonly classified according to the structure and electromagnetic. Structural methods entail optical, ultrasonic, and X-ray visual examination techniques; detection of abnormal heating employing infrared thermographic monitoring and geometric control. Even though highly suitable for the detection of mechanical defects, it often fails to describe electromagnetic behavior of antennas.

Electromagnetic (EM) analysis offers a detailed view of the antenna performance. In the past, conductive testing has been used extensively with transceivers hardwired to measurement instruments [3]. Yet with 5G systems containing increasing miniature transceivers the guiding has become inconvenient if not unworkable. Consequently, there has been a great deal of interest in over-the-air (OTA) alternatives at distances from anechoic chambers associated with direct far-field measurements [4] to compact chamber solutions that mimic far-field conditions [5], and even near-field sampling followed by a mathematical transformation (e.g., [8]). A popular approach is the Relative Element Value (REV) method, which does not require actual wiring for amplitude and phase response measurements although impractical in large arrays as it can be time-consuming [10].

Due to the increase in amount of acquired measurement data, traditional processing approaches are unable to guarantee timely defect detection. As a result, smart technologies such as machine learning, predictive analytics and big data computation are being increasingly incorporated into OTA pipelines [6], [7]. In addition to the automated tests, they support predictive failure modeling which helps ensure more reliable 5G antenna systems.

IV. Machine Learning and Intelligent Methods in Antenna System Diagnostics

The application of neural networks to OTA testing data has become a key area in the development of antenna diagnostics. Deep neural networks (DNNs) analyzing baseband I/Q signals enable rapid and accurate identification of faulty elements in antenna arrays [3]. In Nielsen et al. (2022), it was shown that baseband signals carry sufficient information for the classification of typical failures in mmWave phased arrays.

Convolutional neural networks (CNNs) have also proven effective in radio signal analysis and antenna diagnostics. O'Shea et al. (2016) proposed CNNs for automatic modulation classification [6], while Zheng et al. (2021) applied residual CNNs to detect failures in antenna arrays [7]. These methods not only classify defects but also provide insights into their root causes.

At the same time, big data analytics enable the discovery of hidden patterns within OTA measurement datasets. Techniques such as clustering, association rule mining, and statistical modeling help uncover correlations between antenna design parameters and observed failures, serving as the foundation for building more robust diagnostic and predictive models.

A particularly important direction is predictive analytics, which leverages historical OTA testing data to forecast potential failures. Regression models, decision trees, ensemble methods, and Support Vector Regression have already shown promise in predicting faults in telecommunication systems, paving the way for predictive maintenance strategies that reduce downtime and extend equipment lifespan.

A practical demonstration of ML integration into antenna diagnostics is presented in the work of Kannan et al [11]. where a machine learning–based approach was used to detect faulty elements in phased arrays from sparse far-field measurements. This method substantially reduced diagnosis time while maintaining high accuracy, confirming the viability of ML-enhanced OTA testing pipelines.

In summary, the integration of intelligent methods into electromagnetic testing processes facilitates the transition from conventional defect detection to predictive failure modeling. This shift enhances equipment reliability, lowers maintenance costs, and aligns with the scalability requirements of modern telecommunication networks.

V. Conclutions

The study shows that 5G technologies increase antenna complexity and diagnostic demands. Traditional conductive testing is no longer practical at scale, highlighting the need for refined OTA approaches. Methods such as near-field, far-field, and REV provide essential evaluation tools. Incorporating machine learning enhances data analysis, reduces diagnostic time, and enables predictive failure management, ultimately improving reliability and efficiency in next-generation telecommunication networks.

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