Journal of Electronic Research and Application, 2026, Volume 10, Issue 3
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

Research on RF OTA Test System Optimization During the New Product Introduction Phase of Consumer Electronics

Peng Zhao

Shenzhen SmarTest Measurement & Control Development Limited, Shenzhen 518102, Guangdong, China

Copyright: © 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: Under the trend of high integration and multi-band compatibility in consumer electronics, RF over air testing during the introduction stage of new products faces problems such as large space occupation, poor consistency, and environmental interference. The traditional broadband antenna coupling scheme is difficult to meet the accuracy and efficiency requirements of the production line due to volume redundancy, manual alignment errors, and shielding box attenuation effects. This article proposes an automated OTA testing optimization scheme based on miniaturized dual-frequency monopole antennas, which systematically solves testing pain points through compact MDMA antenna design, six-axis precision control model, and statistical process control verification method. The experiment shows that this scheme reduces the standard deviation of path loss by 40%, reduces the false alarm rate of RF desensitization from 12% to 2.5%, shortens the testing time of a single device to 8 seconds in practical applications, and increases the production yield by 9%, providing an efficient solution for high integration RF testing.

Keywords: Consumer electronics; New product introduction; RF OTA testing; Miniaturized dual frequency monopole antenna

---

Online publication: April 24, 2026

1. Introduction

With the accelerated evolution of the consumer electronics industry towards high integration and multi-band compatibility, emerging technologies such as 5G communication and Wi Fi 6E have put forward strict requirements for RF performance. In the stage of introducing new products, RF over air testing is a key step in verifying wireless communication functionality, and its efficiency and accuracy directly affect mass production yield and cost control [1]. The traditional broadband antenna coupling scheme is difficult to meet the core requirements of compact testing space, consistent results, and anti-interference ability at the production line end due to issues such as volume redundancy, manual alignment errors, and shielding box environmental interference. Therefore, it is urgent to develop an RF OTA testing system that combines miniaturization, automation, and high reliability to support the technological iteration and large-scale application of the consumer electronics industry.

2. Pain point analysis of RF testing in the NPI stage of consumer electronics

2.1. Technical bottlenecks of traditional testing solutions

Traditional RF OTA testing systems face multiple technical bottlenecks during the NPI stage. One of the core issues is the volume redundancy and insufficient frequency band coverage of broadband antennas. Traditional broadband antennas require multi-branch structures or broadband matching networks to achieve multi-band compatibility, resulting in a significant increase in antenna volume and difficulty in adapting to the compact design requirements of consumer electronic devices. At the same time, its radiation efficiency significantly decreases in the high frequency range due to increased dielectric and conductor losses, resulting in insufficient test signal strength [2]. The poor consistency of testing caused by manual alignment errors is another key pain point: traditional solutions rely on manual operation to adjust the antenna pose, which results in mechanical positioning errors and angle deviations, especially in the millimeter wave frequency band, where small deviations can cause path loss fluctuations of over 3dB, seriously reducing the repeatability of test results. The attenuation effect of the shielding box environmental interference on high-frequency signals cannot be ignored: the metal cavity of the shielding box leads to non-linear enhancement of signal attenuation in the high-frequency range due to skin effect and resonance phenomenon, and the opening design of the box is prone to introducing external interference, further deteriorating the signal-to-noise ratio of the testing environment.

2.2. Special requirements for testing systems during the NPI phase

The NPI stage, as a key validation step before mass production of consumer electronics, puts forward differentiated requirements for RF testing systems. The flexibility requirement for quickly switching models on the production line is particularly prominent: the consumer electronics category has a short iteration cycle, and the testing system needs to support modular design to achieve rapid replacement of antennas, fixtures, and testing parameters to meet the needs of multi-model co-production. The ability to perform parallel testing in multiple frequency bands within a limited space is key to improving efficiency: the testing station space on the production line is usually limited, and the testing system needs to integrate multiple frequency band antenna arrays and channel simulators to support synchronous testing in the 2.4G Hz/5G Hz/6G Hz frequency bands, avoiding time waste caused by serial testing in a single frequency band [3]. The necessity of real-time monitoring of RF desensitization phenomenon has also significantly increased: harmonic interference generated by digital circuits inside consumer electronic devices during operation may cover the RF frequency band, resulting in a decrease in receiving sensitivity. The testing system needs to integrate a spectrum analysis module and real-time compensation algorithm to achieve interference source localization and dynamic desensitization, ensuring RF performance stability.

3. Optimization design of RF OTA testing system based on MDMA

3.1. Design of miniaturized dual-frequency monopole antenna

3.1.1. Antenna structure innovation

MDMA adopts dual frequency resonant units and compact layout design, achieving multi-frequency coverage by integrating 2.4G Hz and 5G Hz/6G Hz dual frequency resonant structures. Among them, the 2.4G Hz frequency band uses traditional monopole radiators to reduce input impedance by optimizing the feeding point position [4].

The 5G Hz/6G Hz frequency band expands the high-frequency bandwidth by introducing parasitic patches and slotted structures to form multi-mode resonance. The antenna adopts a planar layout as a whole, and the distance between the radiator and the ground plane is compressed to 3 mm. Combined with the low-loss characteristics of the dielectric substrate, the antenna volume is significantly reduced, which is 65% smaller than traditional broadband antennas.

3.1.2. Radiation efficiency optimization

Optimizing the parameters of MDMA using HFSS electromagnetic simulation software, with a focus on adjusting the parasitic patch length and slot width is the key to balancing impedance matching and radiation efficiency. The simulation results show that the radiation efficiency in the 2.4G Hz frequency band reaches 88%, and in the 5G Hz/6G Hz frequency bands it reaches 86% and 85%, respectively. In the actual verification, the vector network analyzer was used to test the S-parameters of the antenna in a dark room environment, and the radiation power was measured by a spectrum analyzer. The results showed that the actual radiation efficiency in the 2.4G Hz frequency band was 87.2%, 85.8% in the 5G Hz frequency band, and 84.5% in the 6G Hz frequency band, with an error of less than 2% compared to the simulation results, meeting the design specifications.

3.1.3. Verification of multi band coverage capability

To verify the compatibility of MDMA with 2.4G Hz/5G Hz/6G Hz frequency bands, an OTA testing platform was built in a dark room. A standard gain horn antenna was used as the transmission source, and a multi-band continuous wave signal was generated through the signal source. The MDMA under test was polarized by adjusting the polarization direction through a rotating bracket. The test results show that the gain in the 2.4G Hz frequency band is 2.1 dBi, 5G Hz is 3.0 dBi, and 6G Hz is 2.8d Bi; The axial ratio of each frequency band is less than 3 dB, indicating that the antenna has good circular polarization characteristics throughout the entire frequency band and can cover the mainstream communication frequency requirements of consumer electronic devices.

3.2. Development of six axis adjustable precision control model

3.2.1. Mechanical structure design

The six-axis control model adopts a “micrometer level stepper motor + closed-loop feedback” architecture, consisting of X/Y/Z three-way linear motion modules and rotating axes. The linear module uses high-precision ball screws and NSK micro stepper motors, combined with a grating ruler to achieve displacement closed-loop control; The rotating shaft adopts a combination of harmonic reducer and encoder to ensure the accuracy of angle control. The overall mechanical structure adopts aluminum alloy lightweight design, reducing weight by 40% compared to traditional solutions, while meeting the requirements of high-frequency vibration suppression with rigidity.

3.2.2. Software algorithm implementation

The pose compensation algorithm is based on the least squares method to construct an error model. By collecting real-time data from the grating ruler and encoder, the deviation vector between the actual antenna pose and the target pose is calculated, and compensation instructions are generated to drive the motor adjustment. The automated alignment process integrates a machine vision module, which captures antenna feature point images through industrial cameras, processes them using the OpenCV library, extracts center coordinates and angular offsets, feeds them back to the control algorithm for initial positioning, and then initiates closed-loop control to complete precise alignment.

3.2.3. Error analysis

In the repeated positioning accuracy test, MDMA was positioned 100 times in a dark room environment, and the standard deviations of displacement in the X/Y/Z directions were ± 4.2 μm, ± 3.8 μm, and ± 4.5μm, respectively. The standard deviations of angular deviation were ± 0.08 °α axis, ± 0.07 °β axis, and ± 0.09 °γ axis, all of which were better than the design specifications. Long term stability testing shows that after continuous operation for 72 hours, the displacement drift of the system is less than 1 μm and the angle drift is less than 0.02 °, meeting the high-precision testing requirements of the production line end.

3.3. System integration and standardization framework

3.3.1. Hardware modular design

The system adopts the decoupling design of “antenna control acquisition” three modules: the MDMA antenna is connected to the RF front-end through the SMA interface to support rapid replacement; The six axis control unit is independently packaged and provides RS485/EtherCAT communication interfaces; The signal acquisition module integrates VNA and spectrum analyzer functions, supporting multi-channel synchronous sampling. Data exchange between modules is achieved through standardized interfaces, and in the event of a single module failure, only the corresponding unit needs to be replaced, reducing maintenance time to less than 30 minutes.

3.3.2. Standardization of software interfaces

The system software adopts a layered architecture, with the underlying drivers encapsulating hardware operations such as motor control and data acquisition, and providing API interfaces for upper layer calls. Integrated SPC statistical process control module in the middle layer, supporting real-time monitoring of path loss and abnormal alarm; The upper level application interface is developed based on the Qt framework, providing functions such as test parameter configuration, result visualization, and report generation. At the same time, the software reserves LabVIEW/Python secondary development interfaces, and users can implement custom testing process development by calling dynamic link libraries or RESTful APIs, improving system scalability.

4. Verification and optimization of SPC based testing system

4.1. Application of statistical process control theory

4.1.1. Control chart design

To monitor the fluctuation of signal path loss during RF OTA testing, an X-bar/R control chart was used to construct a process stability analysis model [5]. The X-bar chart is used to monitor the mean variation of path loss, while the R chart is used to analyze the range fluctuations within the group. In the experiment, 100 sets of data were collected continuously every 20 tests, and the mean X¯ and range R of each set were calculated, and the control limits were plotted. Through Minitab software analysis, it was found that there were no points exceeding the control limit in the X and R plots of the MDMA system test data, and there were no abnormal patterns such as continuous 7 points on the same side of the centerline or trending arrangement, indicating that the testing process was in a statistically controlled state. The fluctuation of path loss was mainly caused by random factors, and the system stability was significantly better than the traditional scheme.

4.1.2. Process capability analysis

To quantitatively evaluate the stability of the testing system, calculate the process capability indices Cp and Cpk. Taking the standard deviation of path loss as the key quality characteristic, the upper limit of the specification is set at +1.5 dB and the lower limit is set at -1.5 dB. Through calculation, the MDMA system Cp = 2.13 and Cpk = 2.08, indicating that the system has sufficient process capability and the consistency of test results meets the requirements of mass production; However, traditional systems with Cp = 1.32 and Cpk = 1.25 have insufficient process capability and require manual intervention to maintain stability.

4.2. Performance verification in complex dynamic environments

4.2.1. Experimental setup

To simulate the real interference environment of the production line, a dynamic testing platform is built in a darkroom: metal fixtures are arranged within 1 meter around the tested equipment to introduce reflection interference; The dummy model is driven by a servo motor to reciprocate at a speed of 0.5 m/s within a range of 2 m in front of the DUT, generating Doppler frequency shift interference, and turn on the background noise source of the production line to achieve an ambient noise level of -70 dBm [6]. In this environment, 1000 consecutive tests were conducted on the MDMA system and the traditional system, and path loss data was recorded.

4.2.2. Comparison of path loss distribution

The statistical results show that the average path loss of the MDMA system is similar to that of the traditional system, but the standard deviation is significantly reduced. The standard deviation of the MDMA system is 0.18 dB, which is 40% lower than that of the traditional system. Further analysis of frequency domain characteristics reveals that traditional systems experience a 0.12dB increase in path loss fluctuations in the 5G Hz frequency band due to metal fixture resonance, while MDMA systems effectively suppress backward reflection interference by optimizing the antenna radiation pattern; In the scenario of human movement, the MDMA system maintains an antenna polarization matching degree of > 95% due to high-precision pose compensation of the six axis control model, while traditional systems suffer from polarization mismatch caused by manual alignment errors, resulting in an increase of 0.15 dB in path loss fluctuations.

4.3. Real-time compensation model for radio frequency desensitization phenomenon

4.3.1. Mechanism analysis of Desert phenomenon

The phenomenon of radio frequency desensitization is mainly caused by harmonic interference and antenna coupling generated during the operation of digital circuits inside the DUT. Experiments have shown that when the CPU operates at a frequency of 2.4G Hz, its third harmonic may fall into the 6G Hz frequency band receiving channel, resulting in a decrease in receiving sensitivity. Through near-field probe scanning, it was found that the electric field strength of the interference signal at the antenna feeding point can reach -50 dBm, exceeding the system noise floor by 45 dB and causing significant performance degradation.

4.3.2. Attenuation compensation algorithm

Proposing a machine learning-based dynamic threshold adjustment algorithm is crucial. First of all, train historical test data using support vector machines to construct a mapping model between interference intensity and path loss increment; In real-time testing, a spectrum analyzer is used to monitor the interference level in the 6G Hz frequency band. When the interference exceeds the threshold, the compensation module is triggered. Finally, based on the path loss increment predicted by the SVM model, the amplitude adjustment range of the test signal is dynamically adjusted by a digital attenuator within ± 3 dB, with a step size of 0.1 dB, to ensure the accuracy of the receiving sensitivity test.

4.3.3. Verification of compensation effect

Under dynamic interference environment, the CPU runs at full load and conducts 1000 compensation tests on the MDMA system. The results show that the false alarm rate of Desense is 12% without compensation due to abnormal increase in path loss caused by interference. After enabling the compensation algorithm, the false alarm rate decreased to 2.5%, and the compensation response time was less than 50 ms, meeting the real-time testing requirements of the production line. Further analysis revealed that after compensation, the standard deviation of path loss decreased from 0.25 dB to 0.12 dB, and the system's anti-interference ability improved by 52%, verifying the effectiveness of the algorithm.

5. Experimental results and discussion

5.1. Performance indicators of the testing system

The experimental results show that the MDMA system is significantly better than traditional solutions in terms of space occupation and testing efficiency. In terms of space occupation, the MDMA system compresses the overall volume from $0.8m^3$ in traditional systems to $0.28m^3$ through integrated six-axis control modules and compact RF front-end design, reducing the proportion by 65% and effectively reducing the demand for site area in production line layout. In terms of testing efficiency, the MDMA system has reduced the single device testing time from 15 seconds in traditional systems to 8 seconds by optimizing the testing process and improving hardware response speed, resulting in a 46.7% increase in efficiency. Further analysis revealed that the improvement in testing efficiency is mainly due to the dual optimization of RF switching time and mechanical motion time, and the system stability has not decreased due to the increase in speed, verifying the effectiveness of integrated design and high-speed control algorithms.

5.2. Practical application cases

In the NPI stage of a certain brand of smartwatch, the MDMA system demonstrated significant application value. Due to its small antenna size and complex frequency band, the yield rate of traditional testing systems for this product is only 82%. The main problems are excessive path loss fluctuations and Desert misjudgment. After introducing the MDMA system, the high-precision pose compensation and dynamic threshold compensation algorithms of the six-axis control model were used to reduce the standard deviation of path loss to 0.12 dB, the false alarm rate of Desense to 3%, the mass production yield increased to 91%, and the daily production capacity increased by 1200 units. In addition, a 65% reduction in system volume allows the production line to deploy 4 sets of testing equipment simultaneously, further enhancing capacity flexibility.

5.3. Limitations analysis and improvement direction

The current research still has limitations: the adaptability of MDMA systems in the millimeter wave frequency band needs to be optimized. The experiment found that when the test frequency band was raised to 28G Hz, the resonance effect of the metal fixture increased, resulting in a 0.2 dB increase in path loss fluctuations, and high-frequency signals were more sensitive to mechanical motion errors. Future improvement directions include: using low-loss millimeter wave materials to reconstruct testing fixtures to suppress high-frequency resonance; Upgrade the six-axis control model to the nanometer level accuracy to meet the stringent requirements for mechanical stability in the millimeter wave frequency band.

6. Conclusion

The MDMA RF testing system based on SPC and six-axis control proposed in this study achieves quantitative evaluation of testing process stability through X-bar/R control chart and process capability analysis. Combined with dynamic threshold compensation algorithm, it effectively suppresses the Desense phenomenon, significantly improves testing efficiency and mass production yield, and reduces system volume by 65%, meeting the needs of consumer electronics production lines for high precision, high efficiency, and compactness. Future research will focus on adaptive optimization in the millimeter wave frequency band, further expanding the application boundaries of the system in 5G-A/6G scenarios through low-loss material reconstruction testing fixtures and nanoscale motion control upgrades.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Huang Q, Wang P, Liu M, 2025, Research on Key Technologies and RF Testing of 5G RedCap Terminal. Electronic Components and Information Technology, 9(6): 18–20.

[2] Kong G, Yan S, Du W, et al., 2025, Research on Radio Frequency System Measurement Techniques for Microwave Testing. Journal of Physics: Conference Series, 2967(1): 012019.

[3] Ko J, Kim N, Yoo K, et al., 2023, A Low-Phase-Noise RF Up/Down-Converter for Cost-Effective 5G Millimeter-Wave Test Solutions: Special Section on Microwave and Millimeter-Wave Technologies. IEICE Transactions on Electronics, 106(11): 713–717.

[4] Vlad M, Soroush F, Joe F, et al., 2023, Buried RF Sensors for Smart Road Infrastructure: Empirical Communication Range Testing, Propagation by Line of Sight, Diffraction and Reflection Model and Technology Comparison for 868 MHz–2.4 G Hz. Sensors, 23(3): 1669.

[5] Li L, 2017, Research on the Application of SPC in Pneumatic Measurement and Detection System, thesis, Xi'an University of Technology.

[6] Gao Z, Huang L, Wang C, et al., 2025, Production and Testing Scheme for RF Performance of IoT Terminals Based on Cellular Communication Modules. IoT Technology, 15(23): 34–37.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.