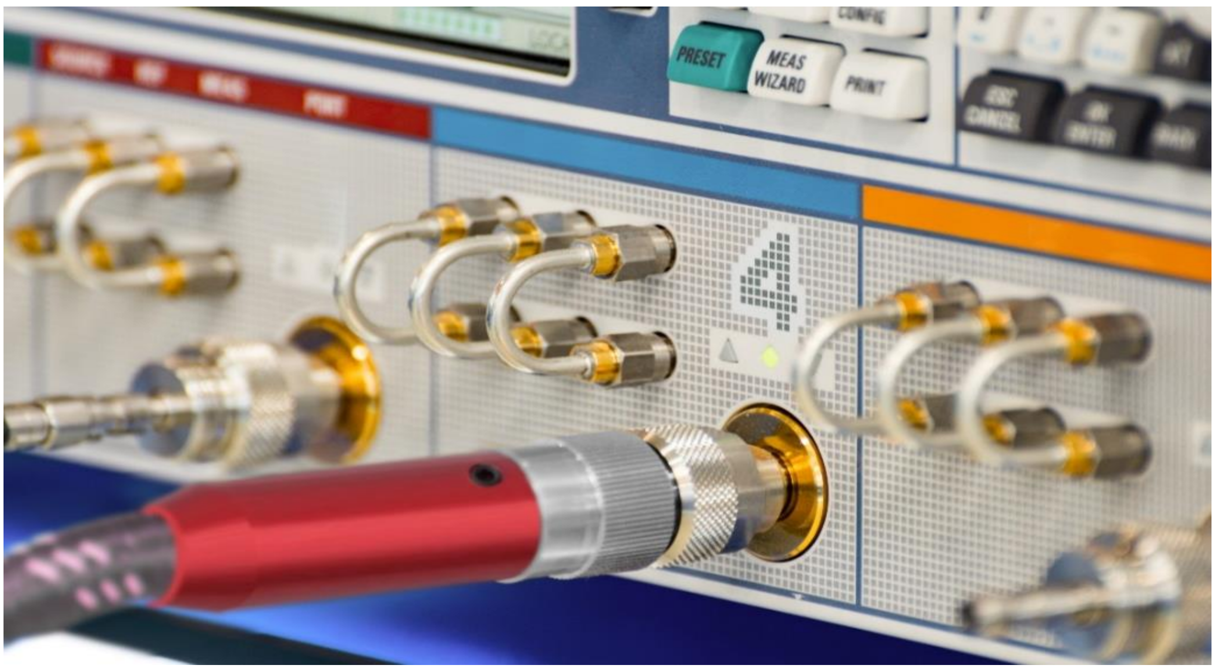
Latest Microwave and Millimeter-Wave Applications Drive Automated Test System Technology & Requirements

White Paper



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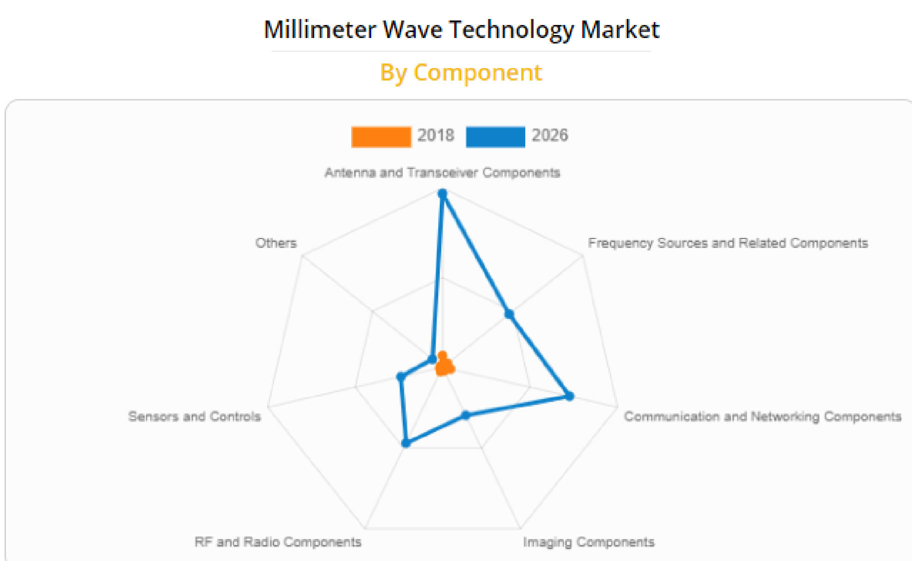
Abstract

Possibly more so now than any time in the past, there are new microwave and millimeter-wave technologies with features and functions that are both higher performance and more diverse than previous technologies. These new technologies are the result of emerging applications with a wide range of new requirements and design constraints. The performance, features, and requirements of these new technologies and applications is, in turn, changing the landscape for microwave production and automated testing. Greater emphasis is now being placed on test system stability and adaptability to a mix of specifications, as well as the need to meet the parameters of advanced millimeter-wave testing, higher test port counts, and test systems with increased levels of integration. Fairview Microwave, a leading provider of RF components, is helping to mitigate the challenges of today's automated test environment with its nearly endless supply of in-stock parts available for immediate shipment.

Introduction

The technology trends of the past few years have led to a surge in microwave and millimeter-wave development. These trends in wireless communications, automotive, military/defense, and satellite communications are being driven by customer demands for systems that are more compact, configurable, efficient, and offer higher performance [1.1, 1.2, 1.3, 1.4]. Moreover, these new devices and systems are being deployed in vast numbers, whereas previous upper microwave and millimeter-wave technologies were deployed in extremely low volumes, with long lead times, and highly customized for customer needs.



The millimeter-wave device and component markets are predicted to grow dramatically in the next several years, with the highest growth areas being communications/networking, antenna/transceiver, RF, and sensors. [1.6]

The result of development to meet these goals is greater levels of integration of RF technology and a rise in the use of microwave and millimeter-wave frequencies for applications that either previously didn't exist or used lower frequency bands. This has led to new challenges for production and automated testing, as production test professionals are having to tackle higher frequency/bandwidth tests, more stringent requirements, and more highly integrated and complex systems, all without exceeding production test footprints or budgets.

Compounding these challenges is the nature of microwave and millimeter-wave testing and test equipment. Typical bench-top devices are not generally well adapted to production test environments, but the higher level of performance they offer is now becoming essential. Furthermore, there are a myriad of interconnect challenges that emerge from higher density tests which are now truly mixed-domain and often require power, analog, RF, and digital testing to be done simultaneously.

The goal of this whitepaper is to discuss production and automated testing challenges being faced in the current wave of new microwave and millimeter-wave technologies and applications. Some insights on solutions and methods that are helping to mitigate these challenges will be shared, along with a few of the emerging applications in microwave and millimeter-wave.

Moving Targets Require New Measurement Techniques & Technologies

For many new microwave and millimeter-wave applications, such as 5G, IoT, active electronically scanned arrays (AESA)/multifunction radar, automotive radar, and satellite communications, the operating frequencies and bandwidths are much higher than the previous generation of technologies for these applications. Moreover, new antenna technologies, such as antenna arrays and active antenna systems (AAS), allow for antennas that can be controlled and configured based on present resource requirements. Another factor to consider is that RF and digital electronics are being more closely integrated, as most modern electronics are now at least digitally-controlled, if not completely controlled by software.

The higher operating frequencies, bandwidth, enhanced digital control, and more complex antennas lead to systems with an extremely high density of ports and interconnect and are much more integrated with semiconductor fabrication processes than ever before. These factors lead to production challenges that are typical of working at higher frequencies and using a larger numbers of ports, and with increased testing at the chip or wafer level.

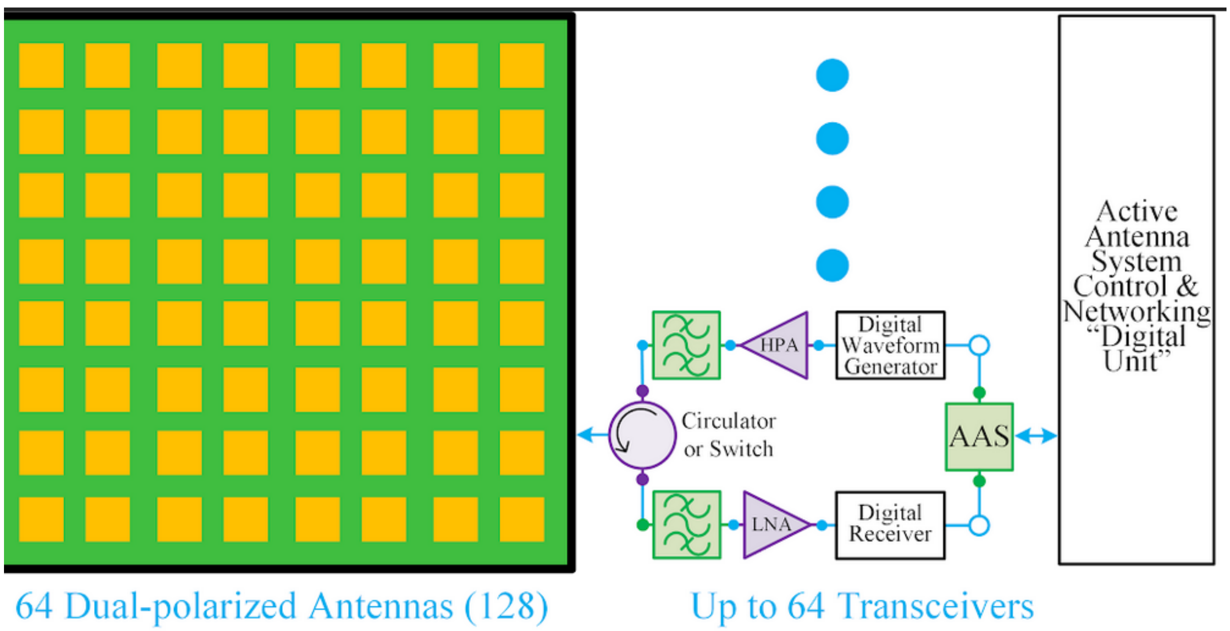
Millimeter-Wave Testing

Due to spectrum congestion and limited bandwidth availability at frequencies below 3 GHz, the latest wireless communication standards have moved to higher frequencies. Though some of the latest 5G new radio (NR) and WiFi have only extended to 6 GHz, other aspects of these standards have enabled the use of frequency bands in the 20 GHz, 30 GHz, 40 GHz, 50 GHz, and 60 GHz spectrum. For other performance reasons mainly related to resolution and possibly the size and footprint of the radars, automotive radar applications have moved from 20 GHz to 70 GHz. To avoid congestion and interference, other radar operation frequencies are also being investigated that operate beyond the X-band. Other reasons for possibly moving radar to higher frequencies is the proportional size reduction of antenna elements and RF components to the operating wavelength.

Also, with greater digital/RF integration, high-speed digital signals carrying an immense amount of data need to be generated, converted, processed, and captured in real-time, which leads to digital signal speeds with frequency components well into the millimeter-wave spectrum. Hence, both RF and digital testing for these applications must consider the significance of electrical and physical phenomenon that emerge at upper microwave and millimeter-wave frequencies as well as the additional constraints on interconnect, design, and material use posed by these frequencies.

In production environments, coaxial cable is very common, because it is a low cost, reliable solution for applications from tens of megahertz to a few gigahertz. However, at upper-microwave and millimeter-wave frequencies, the insertion loss from coaxial connectors and cable assemblies make it difficult to produce a power signal that is high enough for transmission and reflections to occur within the dynamic range of the test equipment. Hence, higher quality coaxial cable may be required, or waveguide interconnect may be necessary to reduce the signal loss and corruption through interconnect.

Though higher frequencies reduce the physical size of coaxial and waveguide interconnect, additional manufacturing and production issues come into play with such small interconnects. With smaller, higher precision interconnect, even small offsets, unclean contacts, and misalignments can dramatically reduce the interconnect performance, even rendering a test inoperable until the problem is solved. This is why in many test scenarios, coaxial spring pins and probes are becoming increasingly common to provide reliable connections to small tests sights on the DUT at high frequencies. For interconnect between test equipment and probe stations, high-quality and phase stable coaxial assemblies and waveguide interconnect are increasingly used and lower-quality coaxial interconnect often doesn’t meet modern performance criteria.



Active antenna systems, such as that used with the latest 4G and upcoming 5G deployments and modern radar systems, involve high numbers of antenna array elements, transceivers, and high-speed digital data transmission in compact assemblies.

More Test Ports Means Higher Density Interconnect

With the advent of MIMO and beamforming, AAS and AESA have emerged that incorporate tens of antennas in a single system. Moreover, these systems are also being integrated with transmit/receive modules (TRMs), beamforming/MIMO circuitry, and digital conversion and processing circuitry. For a single AAS or AESA system, there may be as many as 100 antenna ports, with an equal number of transmit and receive ports, unless subarray techniques are used which reduces the number of TRMs to a fraction of the antenna complexity. Testing such a system often requires multi-domain testing of power, analog, RF, and digital signals, which in turn requires distinct interconnect for each type of signal and a significantly increased number of test ports.

Ensuring that each test port is correctly connected prior to testing is a feat in-and-of-itself for these systems. The cost of installing connectors in test boards is also extremely high. This is why there are removable, end launch clamp/solder coaxial connectors that allow for connector reuse and easy removal of the connectors after testing is complete. Probing of PCBs is also increasingly common to avoid having to mate coaxial or waveguide connectors, and probing allows for inline testing of PCB traces in either ground-signal or ground-signal-ground configurations. Both 3.5 mm coaxial probes reaching 20 GHz or 2.92 mm coaxial probes reaching 40 GHz are commercially available. Used in tandem with a probe positioner and skew-matched coaxial cable assembly, consistent and reliable RF and digital signal probing can be performed, which may dramatically speed up production testing while improving test repeatability.

More Integration Means More Wafer-Level Testing

More compact interconnect, be it end-launch removable coaxial connectors or probes, help to address higher level assembled devices and systems; but in many cases now, greater levels of RF integration requires chip- or wafer-level probing. In many situations, wafer-level probing is either done in the early prototype stage by hand during proof-of-concept or characterization testing, or with automated testers in semiconductor fabrication facilities for quality inspections. The latest trend of chip- and wafer-level testing for microwave and millimeter-wave applications involves complex multi-port probes (some with over 30 RF contacts) [1.5].

These probes now support several coaxial ports, typically 50 ohm MC, SMB, SMA, 3.5mm, or 2.92mm, and potentially coaxial interconnect with higher frequency capability. There are many cases now where new complex wafer probes support waveguide, coaxial, and digital signal interconnect. With the increasing speed of digital signals, microwave and millimeter-wave coaxial assemblies are increasingly used as digital signal interconnect.

Power and possibly analog signal tests are also often simultaneously conducted to ensure proper biasing performance and efficiency. This means that multi-domain probing and test systems are needed for complex System-on-Chip or System-in-Package (SoC/SiP) testing.

Ensuring Test System Stability

Though power, analog, and digital signal production tests do need to be made with great precision, microwave and millimeter-wave testing requires another level of calibration and sometimes “zeroing” prior to a test to ensure measurement consistency and repeatability. With the extremely high frequencies used in modern 5G, IoT, automotive radar, and multi-function radar, the test instruments and testing environment is comparatively highly variable and often requires frequency calibration (often only after several minutes of testing). In a production environment calibration delays are inconvenient and costly, they also ad wear to the probing and interconnect and may also require calibration standards and accessories that also require replacement.

At microwave and millimeter-wave frequencies, calibration and de-embeding of test fixtures is much more critical than at lower frequencies. Moreover, the sensitivity of calibration to error means that it is often essential to calibrate to the DUT plane, which for wafer testing requires on-wafer or in-socket standards. Moreover, a vector measurement system is preferred for de-embedding the test environment and parasitics from test results. In the case of wafer-level testing, multiple layers of calibration are also important, which includes the instrument, interface, and probe card/device interface board layer.

These efforts will be wasted time though if the interconnect for the test system is not as stable as the instruments. This is why phase stable cabling is useful to ensure testing stability and longevity of calibration. Waveguide interconnect is also useful in ensuring stable measurements, as the fixturing and physical behavior of waveguide (being rigid metal) minimizes variation of electrical performance to vibration and thermal fluctuations in the surrounding environment.

Adapting to High Mix Low Volume

Prototype and characterization laboratories are often equipped to handle a variety of testing scenarios. This includes a diversity of test equipment and accessories that allow for testing devices and components under varying conditions. Production and ATE testing, however, is usually extremely specific testing that is ideally run with as little setup and configuration as possible. Setup and reconfiguration time is down time, which incurs cost and can delay production schedules. Modern devices and systems are requiring much more complex test routines, often with unique needs. This trend places production test system operators, especially automated test system operators, in a challenging situation, as the new model of business appears to be a hybrid volume and high-mix format.

Previous generations of microwave and millimeter-wave equipment were often only produced in small volumes and were highly customized and catered to customer-specific requirements, standards, and specifications. In many cases, production testing for the previous generation of high-frequency devices and systems was performed on the same test equipment as prototyping and development. This was mostly due to the cost of the equipment itself and the expertise required to perform proper setup and calibration of the equipment and DUT.

Now the same challenges associated with microwave and millimeter-wave production testing are being transferred to mass production test facilities, as greater volumes of these devices and systems are in demand. However, cost, test times, testing footprint, setup complexity, and operational complexity must still be kept to a minimum to enable viable production testing. New types of test equipment, such as modular, portable, and software-defined radio (SDR) style equipment help production facilities rapidly adapt to changing requirements, but interconnect with new DUTs is always a challenge. Many times custom cable assemblies, waveguides, and adapters are urgently needed, though the interconnect industry at large is still set up to respond to quotes in a relatively slow manner. This is why same-day shipping of custom coaxial cable assemblies, waveguide, adapters, and accessories is essential to the modern microwave and millimeter-wave industry. Without such services, production test operators would have to wait weeks, or even months, to receive the right interconnect for a new product test or for failure replacement.

Modern Production & Automated Test System Requirements

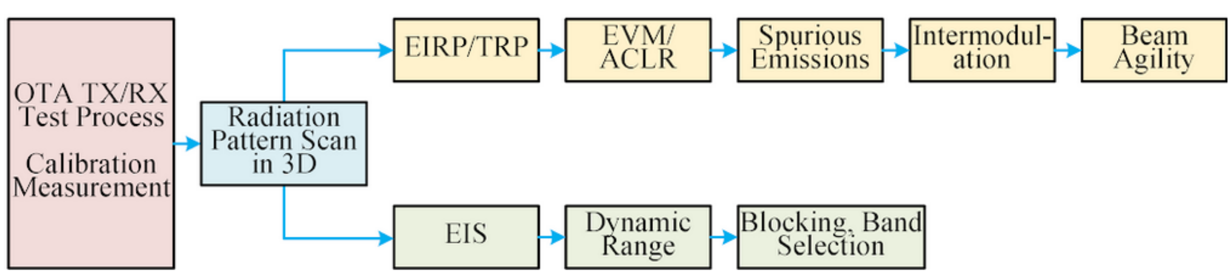
The production test challenges for microwave and millimeter-wave devices and systems are largely in response to the unique application requirements emerging in this space. Generally, the market for these applications has rapidly shifted from a low-volume, long-lead-time market, to a fast-paced and competitive landscape where production testing can make or break a product.

The following sections discuss the trends and nuances of production testing for key emerging and evolving microwave and millimeter-wave applications. These applications were chosen because they have become the main drivers of change for microwave and millimeter-wave production testing – a trend that is likely to continue and even accelerate.

5G/WiGig/IoT

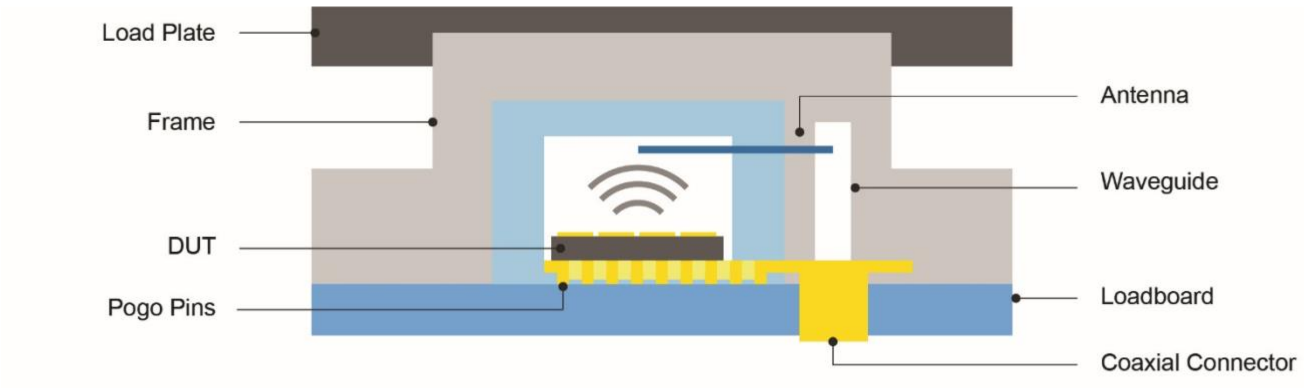
To avoid congestion at frequencies below 6 GHz and to enable higher throughput with greater available bandwidth, wireless communication standards are now targeting spectrum above 20 GHz for next-generation wireless communication [2.1, 2.2, 2.3]. Until this leap, however, RF production testing and high-volume manufacturing (HVM) wafer production typically didn't exceed 6 GHz, as mobile phones and other portable electronic devices (PEDs) with radio frequency integrated circuit (RFIC) chips used only sub-6 GHz LTE and cellular bands, 2.4 GHz Bluetooth/WiFi, and 5 GHz WiFi.

Now, production testing floors and HVM wafer production testing must cope with frequencies as high as 67 GHz and single-channel bandwidths as high as 400 MHz. New 5G devices will require compatibility with sub-6 GHz and millimeter-wave bands, MIMO, carrier aggregation (CA), and other advanced features which are predicted to dramatically increase both testing time and cost. Moreover, it is likely that a large portion of user equipment (UE) and PED testing will have a variety of wireless communication standards to now consider, such as Bluetooth, 2.4 GHz/5 GHz WiFi, and NFC.



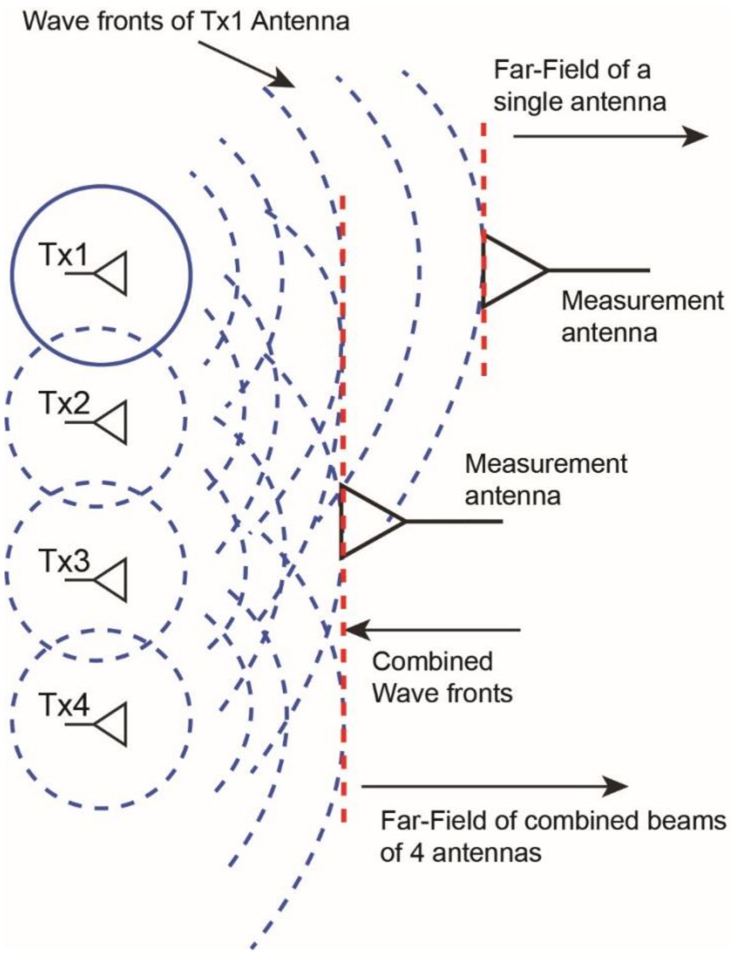
OTA TX/RX Testing procedures for 5G AAS

Multi-site RF testing is likely to be necessary to meet testing cost and time constraints. With a max of 64 RF channels per device, an x8 parallel 5G device test would increase the simultaneous channel count to 256 RF channels. Switches, combiners, baluns, and other methods may be used to reduce the channel count for testers, but these methods also include trade-offs of measurement accuracy and time [2.4, 2.5, 2.6]. It may be prudent to employ multi-site calibration during multi-DUT testing to ensure measurement accuracy, for which short-open-load-through (SOLT) calibration with RF calibration substrates would match the multi-site test configuration. Other methods, including over-the-air (OTA) antenna coupling have been suggested for 5G wafer testing, in which the measurement coupler would be placed within 100 micro-meters of the 5G antenna, using wafer probe technology for positioning. Such innovative methods may be the only viable way to achieve low-cost production testing of 5G devices, since early runs of 5G devices may exhibit lower than standard yields, making packaging tests much more expensive and prone to greater errors than wafer-level testing [2.7, 2.8].



An RFIC OTA multi-site test socket with NF test antenna

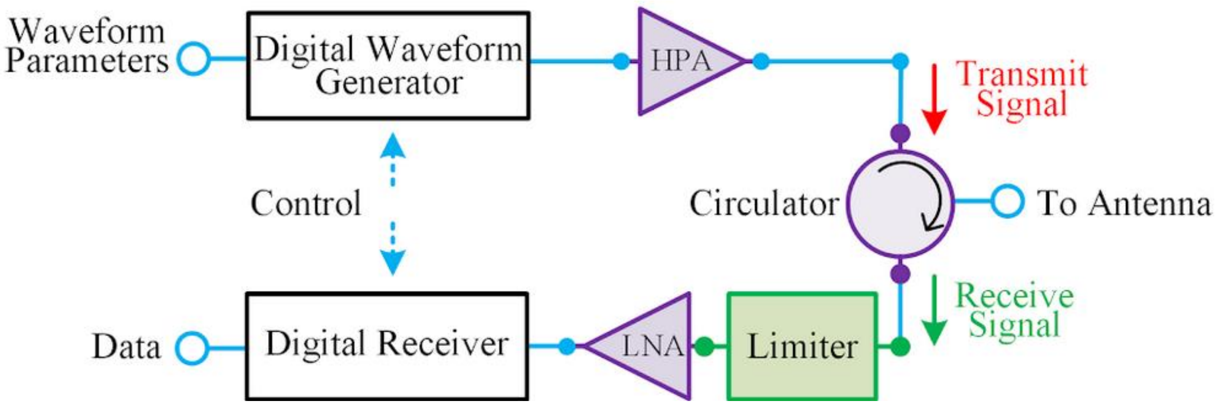
Production testing of complete 5G AAS is also posing a challenge to the industry, because early 3GPP standards and testing documents don't clearly outline testing measures to account for the performance of AAS. The industry appears to be transitioning away from wired RF testing of AAS and 5G systems to OTA testing in highly-capable anechoic chambers built for one of several OTA testing techniques. There are many challenges associated with OTA testing of microwave and millimeter-wave AAS, including near-field (NF) and far-field (FF) discrepancies between a single antenna element and an array antenna, as well as the complexities and accuracy constraints of NF to FF conversion models. Though the industry has yet to converge on a standardized testing approach, and likely several methods will persist into the future, these new AAS and 5G testing systems will likely require several broadband probes, precision interconnect, and complex test equipment setups that can handle the frequency range, dynamic range, bandwidths, and modulation complexity of the latest generation of communication standards.



MIMO/beamforming antenna exhibit a different far-field zone for the antenna array compared to that of an individual antenna.

AESA & Multi-Function Radar

AESA and Multi-Function Array Radar (MFAR) have transitioned from the niche role of enabling next-generation multi-role fighters, to a capability enhancement and method of preserving the utility of older aircraft and radar [3.1]. The deployment of AESA and MFAR have skyrocketed in recent years, and AESA and MFAR are now being installed as critical systems on military helicopters, naval vessels, and land mobile systems. The increased use of AESA and MFAR have also changed manufacturing approaches to meet demand, while still maintaining quality and military specifications. AESA and MFAR are comprised of an antenna array with tens to over one hundred elements, and Transmit/Receive Modules (TRMs) that drive either one or a cluster of antenna elements. Modern AESA and MFAR are generally frequency-agile and broadband systems with features such as Low-Probability-of-Detection/Low-Probability-of-Intercept (LPD/LPI) to avoid detection and mitigate jamming/spoofing through use of complex modulation schemes. The results of which are production testing and quality conformance to MIL-SPEC for each device/component and the overall AESA and MFAR system. This often includes high-precision testing of amplifiers, circulators/isolators, limiters, antenna modules, Digital Receiver Technology/Analog-to-Digital Converters (ADCs), Digital Waveform Generators/Digital-to-Analog Converters (DACs), and the subsequent waveform parameter systems and radar data analysis technology. As co-site interference, jamming, and isolation are key requirements for these systems, additional stringent Electromagnetic Compliance (EMC) testing to MIL-SPEC is also necessary [3.2, 3.3].



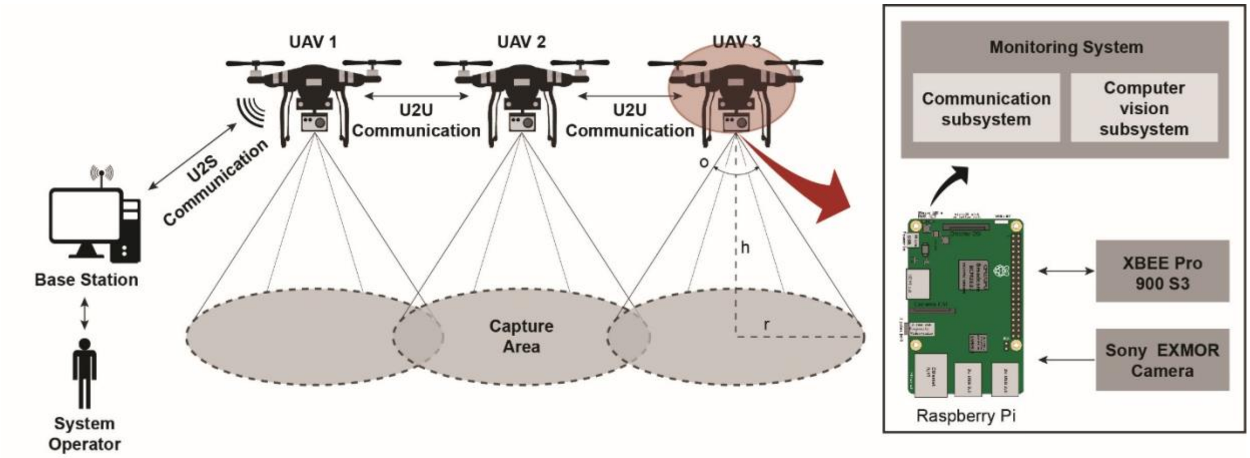
A high-level Transmit/Receive Module (TRM) diagram for an AESA/MFAR

Military radars have also been developed that exceed typical C-band and X-band frequencies to avoid interference with the increasingly cluttered lower frequency military, industrial, and commercial bands. New Ku-band, K-band, and Ka-band systems are also being deployed. Higher frequency radar enables greater resolution and discrimination among small targets, such as drones and drone swarms. Fairview Microwave offers a wide variety of in-stock components supporting K-band and Ka-band frequencies that are available for same day shipment, including power amplifiers, low noise amplifiers, switches, limiters, mixers, oscillators, detectors, circulators, couplers, attenuators, filters, and power dividers. Many new military radars are capable of multi-radar band operation and even wireless communication. These frequency capabilities and requirements for frequency agility create a multitude of challenges during production testing, some of which are similar to those found in newer 5G AAS production testing, though AESA and MFAR are subject to even more stringent performance standards and require much higher dynamic-range testing.

Generally, production testing systems for AESA and MFAR are custom systems that incur both a high cost of development and of operation. Innovative testing methods involving anechoic chambers with arrays of antenna probes and sophisticated test equipment setups are also being pioneered to overcome some of the production challenges associated with testing AESA and MFAR with complex and dynamic beam-pattern capabilities. Though this may change, as modular, portable, and software programmable/configurable RF test equipment operating to higher frequencies is becoming available with performance levels that may soon meet requirements for AESA and MFAR. Some test equipment manufacturers are even making software configurable extension units to enable more complex testing of assemblies and systems, such as AESA and MFAR TRMs [3.4].

Unmanned Systems Communications & Sensors

Unmanned Systems, including Unmanned Aerial Vehicles (UAVs), Unmanned Naval Systems (UNS), and Unmanned Land Systems (ULS), are becoming increasingly common for surveillance, protecting military personnel, thwarting other unmanned systems, and more critical roles [4.1, 4.2, 4.3]. As unmanned systems become more common, their production quantities are increasing, as is the complexity and performance of their onboard systems. Common standards for unmanned systems are MIL-STD-461 for Electromagnetic Interference (EMI)/EMC and MIL-STD-217 for reliability, along with other radio navigation standards common to many unmanned platforms.



UAS networks, or drone swarms, are a proposed method of surveillance for a variety of applications where individual UAS or human operators may be less efficient or effective. [4.3];
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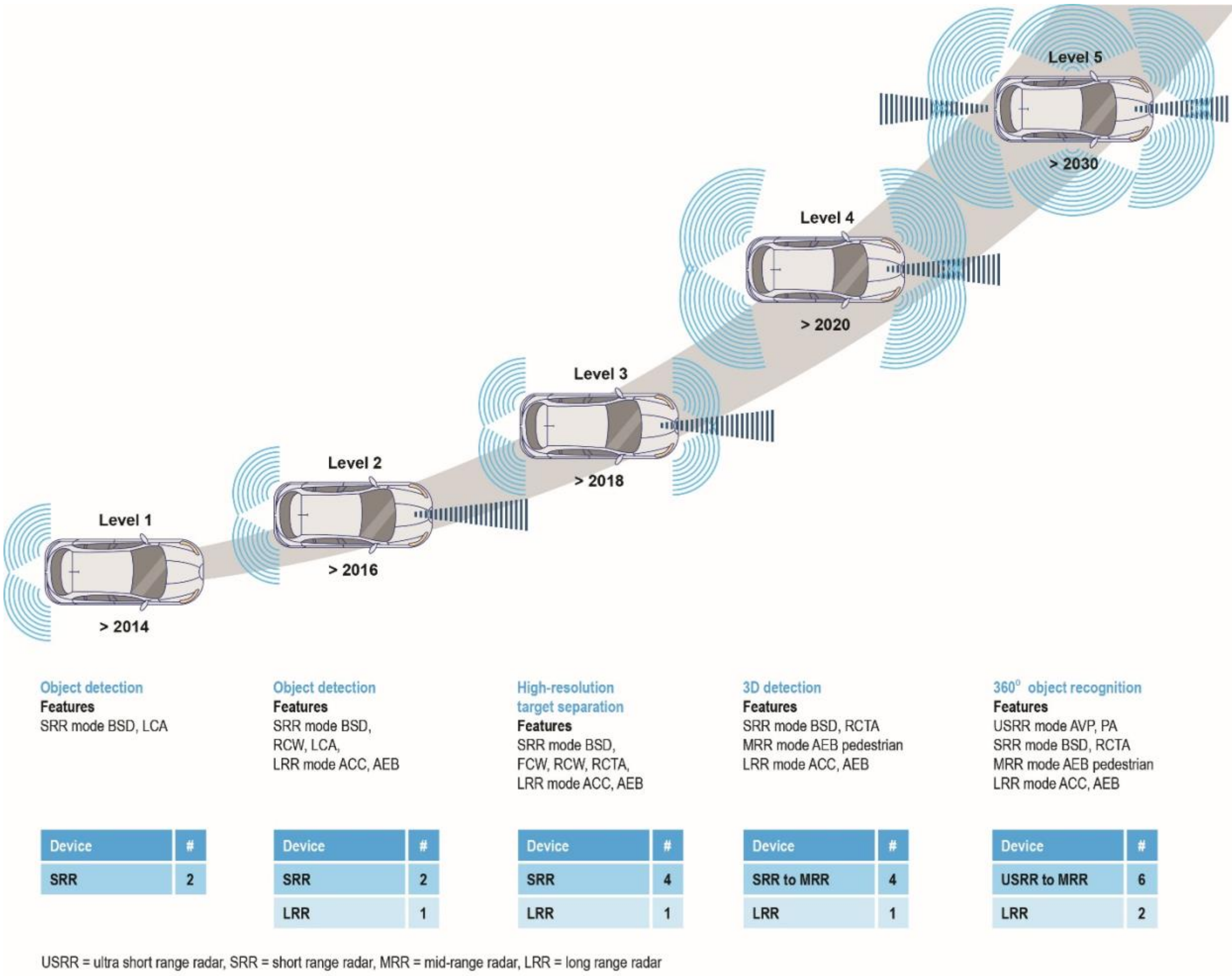
Unmanned systems require both reliable and capable sensor systems as well as communication links that are often extremely compact and face power constraints. Given that many unmanned systems are used in place of endangering personnel, they are also subject to some of the most extreme environments during missions. Though the demands on unmanned systems are extensive, the cost, which includes production testing, is still a significant constraint for these units.

Automotive Radar & Vehicle Communication Systems

Though early autonomous vehicle tests have demonstrated the feasibility of the technology, it will be a while before truly autonomous vehicle systems are actively deployed around the world [5.1]. In preparation for the future of autonomous vehicle systems and the whole infrastructure dedicated to enhancing vehicle-to-everything (V2X) communications, production testing systems that can test both short range radar, long range radar, and new vehicle communication standards (i.e. future 5G vehicle communications) must be able to meet stringent automotive safety standards, some of which are not even developed yet [5.2, 5.3, 5.4, 5.5].



Trends in the number and types of automotive radar and sensor systems. [5.1]

Currently, Advanced Driver Assistance Systems (ADAS) that rely on sensor fusion and machine learning present a sizable challenge for production testing. Adaptive Cruise Control (AAC) and Autonomous Emergency Braking (AEB) features are commonly employed by these systems, and they are exceedingly difficult to test using typical production test environments. Hence, Hardware-in-the-Loop (HIL) testing methods are increasingly being used to verify performance and meet emerging ADAS and autonomous vehicle standards.

Conclusion

The microwave and millimeter-wave device, component, and systems market is going through dramatic changes as new, complex applications emerge with augmented performance requirements and at a rate never seen before. Rushing to face this onslaught, production test facilities are having to adapt to new spectrum, bandwidth, and overall performance requirements for these applications while minimizing costs. There is also the general difficulty of maintaining reliable and stable performance of test equipment at upper-microwave and millimeter-wave bands.

A key challenge for production test labs is sourcing interconnect that will meet microwave/millimeter-wave testing requirements without being delayed weeks or months due to long lead times. This is where Fairview Microwave's same-day shipping of interconnect, including custom coaxial cable assemblies, shines in helping to meet the urgent component needs of production test facilities around the globe. From coaxial assemblies and waveguides to connectors and adapters of every type and style, Fairview Microwave has nearly 1 million RF, microwave, and millimeter-wave components in-stock and ready to ship today.

Resources

1. **Microwave & Millimeter-wave Market Trends**
    1. Millimeter Wave Technology Market [By Product (Scanner Systems, Radar and Satellite Communications Systems, Telecommunication Equipment) By Frequency Band (24 GHz and 57 GHz, 57 GHz and 86 GHz, 86 GHz and 300 GHz) By End-User (Mobile & Telecom, Healthcare, Commercial, Industrial, Consumer, Automotive, Defense, Others), By Regions]: Market Size & Forecast, 2018 - 2026
    2. Millimeter Wave Technology - Global Market Outlook (2017-2026)
    3. RF Tunable Filter Market by Type (Band Pass and Band Reject), Tuning Mechanism (Mechanical and Electronic), Tuning Component (DTC, SAW, and SMD Variant), End-Use (SDR, RF Amplifiers, and Radar Systems), Application, Geography - Global Forecast to 2025
    4. Emerging trends in advanced rf/microwave filters for wireless applications, part i
    5. Improving Wafer-Level S-parameters Measurement Accuracy and Stability with Probe-Tip Power Calibration up to 110 GHz for 5G Applications
    6. Millimeter Wave Technology Market by Product Type (Scanner Systems, Radar & Satellite Communication Systems, and Telecommunication Equipment), License Type (Light Licensed Frequency, Unlicensed Frequency, and Fully Licensed Frequency) Frequency Band (Below 57GHz, Between 57GHz & 300GHz, and Above 300GHz) Application (Telecommunication, Military & Defense, Automotive, Radio Astronomy, Consumer Industry, Commercial, and Others): Global Opportunity Analysis and Industry Forecast, 2019-2026
2. **5G/WiGig/IoT**
    1. ITU-R M.2083-0
    2. ITU-T K.116
    3. Heterogeneous Integration Roadmap 2019 Edition
    4. Testing the 5G New Radio
    5. Gaps In 5G Test
    6. "New test methodologies for 5G wafer high-volume production," Chip Scale Review January-February 2019
    7. Probe selection for over-the-air test in 5G base stations with massive multiple-input multiple-output
    8. RF Module Test Challenges
3. **AESA/Modular Radar**
    1. The Role and Trending Requirements of RF Limiters in Multifunctional AESA Radar
    2. Active Electronically Steered Array (AESA) Antenna Testing

    3. Key considerations in radar test
    4. Improving T/R Module Test Accuracy and Throughput

4. **Unmanned Systems**
    1. NASA's first-of-kind tests look to manage drones in cities
    2. Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress
    3. Performance Evaluation of Multi-UAV Network Applied to Scanning Rocket Impact Area†

5. **Automotive Radar**
    1. Automotive Radar 2020-2040: Devices, Materials, Processing, AI, Markets, and Players
    2. Overcome millimeter-wave Automotive Radar Testing Challenges
    3. NHTSA Radar Congestion Study
    4. Automotive millimeter-wave Radar EMC Test Developments and Challenges
    5. ELECTRONIC PERVASIVENESS IN VEHICLES BRINGS EMI CHALLENGES

Glossary

Term	Description
5G	Fifth-generation Cellular Communications
AAC	Adaptive Cruise Control
AAS	Advanced antenna systems or active antenna systems
ADAS	Advanced driver assistance system
ADC	Analog to digital converter
AEB	Autonomous Emergency Braking
AESA	Active Electronically Scanned Array
AUV	Autonomous Underwater Vehicles
C-band	4 GHz to 8 GHz
CA	Carrier Aggregation
CPE	Customer Premise Equipment
DAC	Digital to analog converter
ECM	Electronic Countermeasures
EMC	Electromagnetic compliance
EMI	Electromagnetic interference
EW	Electronic Warfare
FF	Far-field
HALE	High-altitude Long-Endurance
HIL	Hardware-in-the-loop
HIL	Hardware-in-the-loop
IEEE	Institute of Electrical and Electronics Engineers
K-band	18 GHz to 27 GHz
Ka-band	27 GHz to 40 GHz
Ku-band	12 GHz to 18 GHz
LDUUV	Large Displacement Unmanned Underwater Vehicles
LPD	Low probability of detection
LPI	Low probability of intercept
MALE	Medium-Altitude Long-Endurance
MAV	Micro-air vehicle
MFR/MFAR	Multi-function Radar
Mil-Spec	Military specification
MIMO	Multi-input Multi-output
mmW	Millimeter-wave
MUSV	Medium Unmanned Surface Vehicles
NF	Near-field
OMFV	Optionally Manned Fighting Vehicle
OTA	Over-the-air
PED	Portable Electronic Device
ROA	Remoately Operated Aircraft
RPA/RPV	Remoately Piloted Aircraft/Remotely Piloted Vehicle
RPS	Remotely Piloted System
RX	Recieve or receiver
sUAS/sUAV	Small Unmanned Arial System/small Unmanned Aerial Vehicle
TRM	Transmit/Recieve Module
TX	Transmit or Transmitter
UAS/UAV	Unmanned Arieal System/Unmanned Aerial Vehicle
UCAV	Unmanned Compact Air Vehicle
UE	User Equipment
UGCV	Unmanned Ground Combat Vehicle
UGS/UGV	Unmanned Ground System/Unmanned Ground Vehicle
ULS/ULV	Unmanned Land System/Unmanned Land Vehicle
UNS/UNV	Unmanned Naval System/Unmanned Naval Vehicle
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
VRTS	Vehicle Radar Test System
WiGig	IEEE 802.11ad
X-band	8 GHz to 12 GHz
XLUUV	Extra-large Unmanned Surface Vehicles