TECHNICAL BRIEF

Realizing 5G and Wi-Fi 6E Networks With Evolving Programmable Test Systems

It is well understood that the technologies used to usher in next-generation 5G and Wi-Fi 6E wireless networks are revolutionary in terms of spectrum usage, component and IC advancement on the substrate- and packaging-levels. In order to meet the seemingly unreachable 5G key performance indicators (KPIs) a mix of technological leaps and iterative improvements on the previous cellular infrastructure had to be realized. Much of the improvements seen for 5G and Wi-Fi 6 revolve heavily around the use of Multi-input Multi-output (MIMO) in its various forms. Along with the widespread adoption of any of these technologies, there is the need to understand precisely how these signals perform in the myriad of environments they will be deployed in. From small, rack-mount switched matrices with step attenuators, amplifiers, combiners and splitters to hulking massive MIMO (mMIMO) test beds, these test systems are critical for network architects to obtain a comprehensive understanding of the functionalities of a 5G NR signal in a complex transmission environment. This Tech Brief will provide an understanding of the various key factors of modern wireless architectures, and introduce some novel ideas for testing and development of these systems.

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Understanding precisely how a 5G or Wi-Fi 6 device functions in the array of potential propagation environments is critical to a wireless infrastructure deployment. Flexible handover and MIMO test systems are critical to ensure a reliable connection regardless of potential signal obstacles, traffic load, and interference.

The modern transmission environment and enhancements that enable the 5G and Wi-Fi 6/6E performance

The monumental task of meeting these KPIs regardless of signal environment calls for creativity in network topologies, base station technologies, and backhaul architecture. There are several environmental factors that dramatically impact user experience when attempting to connect to the cellular network:

- Free space path loss
- Interference
- Fading from multipath or shadowing
- Fast-moving terminal
- Geographic accessibility to a cell tower

The intrinsic path loss of a signal propagating through free space dramatically increases with frequency. This has been the critical concern around small cell installations to serve dense urban locations. Not only do mmWave signals suffer from rapid attenuation in free space with a much higher atmospheric absorption, these signals are also almost incapable of diffracting around objects as their longer wavelength, sub-6GHz counterparts did. Instead, mmWave signals scatter on even relatively smooth surfaces with tiny surface variations and are entirely attenuated through most objects. This calls for line-of-sight communications and beamforming with a proper spatial representation of the channel for accurate beam alignment. Meeting the KPIs also means using a microwave backhaul infrastructure, deep fiber installation, or even a non-terrestrial 5G base station (aka: a satellite) to extend connectivity to the geographically distant communities in rural regions.

The total number of connected IoT devices is expected to reach 27 billion by 2025 while the number of mobile devices is anticipated to be 18.22

billion. Interference from the ever-increasing device congestion is a continual concern for device manufacturers. Techniques such as self-interference cancellation, dynamic spectrum sharing (DSS), and remote interference management (RIM) aim to minimize these issues. Even multi-user MIMO (MU-MIMO) and the scaled up version of MU-MIMO—massive MIMO (mMIMO)—both suffer from co-channel interference requiring nearly perfect channel state information (CSI), or the assessment of the signal degrading occurrences from the transmitter to receiver. This includes the potential for scattering, fading, and power decay.

Environmental obstacles are undeniable considerations in channel modeling; trees, buildings, foliage, and rain all contribute to fading. MIMO enhancements are incorporated in virtually every 5G 3GPP release in both the sub-6GHz and millimeter-wave frequencies with a multitude of antenna elements and radio architectures. Wi-Fi 5, or 802.11ac, was the first Wi-Fi standard to introduce the use of multi-user MIMO where the access point (AP) is able to now form multiple beams towards each client while simultaneously transmitting information to each one in a downlink. Wi-Fi 6, operates on the same MU-MIMO or spatial multiplexing principle but instead improves the network performance by incorporating the orthogonal frequency-division multiple access (OFDMA) modulation scheme, higher order quadrature amplitude modulation (1024-QAM), as well as both uplink and downlink MU-MIMO. Wi-Fi 6 E extends the Wi-Fi spectrum into the 6 GHz bands (5.925 to 7.125 GHz) to both open up more spectrum for Wi-Fi and bolster 5G unlicensed NR (NR-U) deployments.

Vehicle to everything (V2X) and mobile terminals require the use of speedy handovers from one base station to another and is a fundamental building block to future autonomous driving that will rely on ultra-low latency communications and a ultra-reliable signal. This includes all permutations of potential links to and from the automobile including vehicle-to-vehicle communications (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) communication. Extremely fast moving vehicles such as high speed trains (HST) and planes have more stringent handover requirements due to their rapid fading profile. Covering the full range of environments requires a fundamentally shifted radio networking architecture to support the variety of base station topologies (e.g., small cell, mMIMO, satellite, eNodeB, etc).

So, how do we test these systems in a lab environment?

Switched matrices are the mainstay for simulating the effects an environment would have on RF transmission. Engineers utilize a series of power dividers and combiners along with individually controlled programmable attenuators on every path through the matrix (Figure 1).

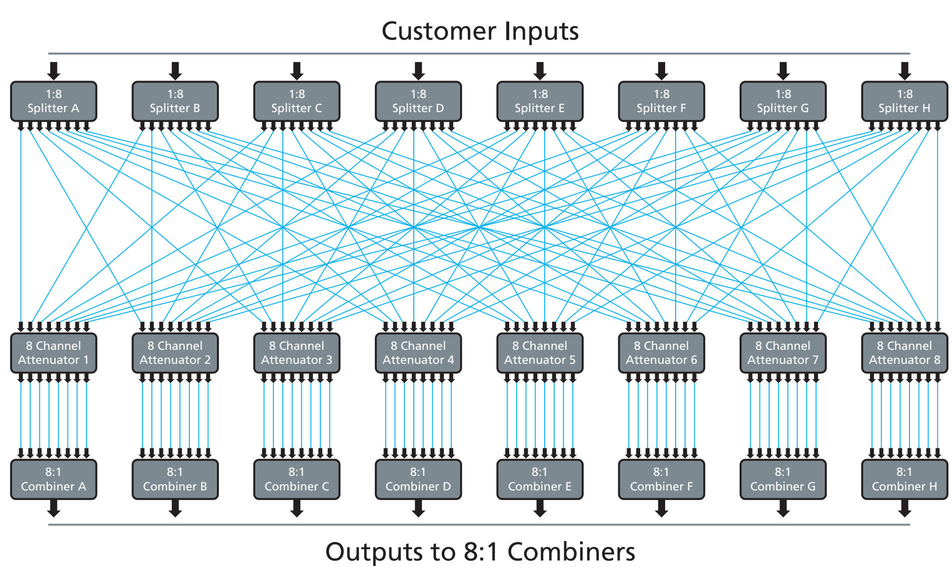


Figure 1. 8x8 attenuation matrix.

This way, every input signal could be attenuated at different levels to, for instance, simulate free space path loss, fading, or signal attenuation as the device moves away from the signal source. With fast switching attenuators the RF switch matrix can be programmed to simulate fast and slow fading, shadowing, multipath, interference, and a slew of other propagation phenomena by adjusting the attenuation value over an allotted time frame. Imitating the real world effects of mobile fading where a fast-moving device (e.g., vehicle, train, plane, etc) might be passing through the coverage area of more than one base station can be extrapolated from the known variables of the location of the base station, the speed and location of the moving device, the carrier frequency of the signal, and the antenna gain for the receivers and transmitters. The attenuation between these various nodes can be calculated using the free-space path loss model or Friis equation. Testing handover in these systems would require a switched matrix with multiple inputs where each input represents a different base station while the output is the receiving device (Figure 2).

MIMO testing challenges

The massive benefits of MIMO

Cellular technologies have long taken advantage of MIMO for spatial diversity to alleviate the issue of fading. Spatial diversity uses different channels to convey identical streams of information from the transmit antenna(s) to the receive antenna(s). Using a multitude of antennas at both the transmitter and receiver to send redundant data transmissions in parallel along multiple radio paths increases both link reliability and range. Transmitting the same signal over multiple different paths takes advantage of diversity gain while transmitting multiple signals over different paths offers multiplexing gain. Multi-User MIMO (MU-MIMO) instead takes advantage of multiplexing gain in order to send independent streams of information to different receivers.

This spatial multiplexing technique is the fundamental idea behind massive MIMO -- utilizing a high number of concurrent transmissions to user terminals through narrow, spatially focused beams. This system takes advantage of both diversity and multiplexing gain on a massive scale, increasing capacity without the use of extra bandwidth or transmit power. However, compared to traditional MU-MIMO systems, mMIMO offers much higher throughput, noise resistance, energy efficiency, link stability, and antenna correlation with a lower bit error rate (BER). This comes at the cost of a high system complexity and cost with serious design considerations around antenna coupling and pilot contamination. Pilot sequences allow for rapid channel estimation at the receiver by sending out a quick signal, a quick channel estimation is generated through the information gained by the received signal. However, iterative usage of these sequences in more than one co-channel cell can rapidly degrade system performance as the system relies upon an accurate CSI.

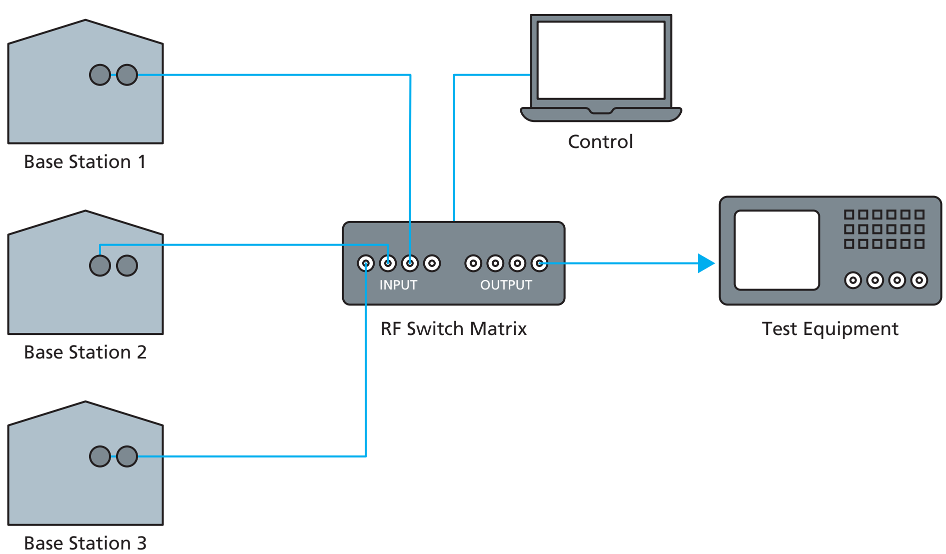
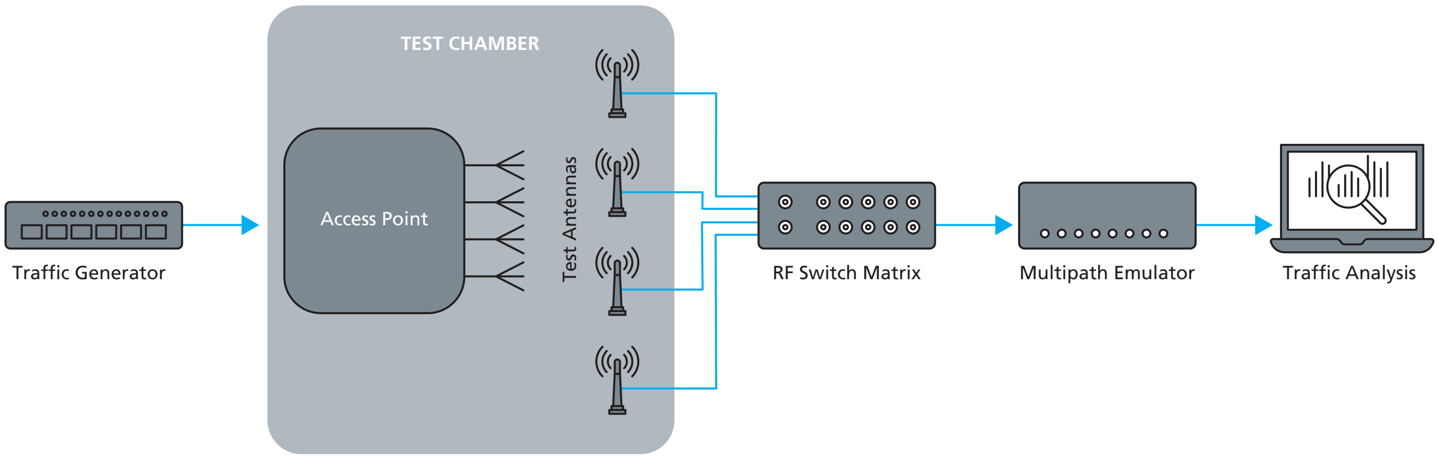


Figure 2. In handover test systems each input correlates to a different base station while the output signal would refer to the received signal at the terminal. Large switch matrices could take in large amounts of customer inputs, or base station signals, and attenuate them accordingly to simulate a high speed train, aircraft, or any other fast moving vehicle.

Figure 3. Sample Wi-Fi MIMO test setup.



For this reason recent 3GPP NR releases are enhancements on MIMO, often in regards to the CSI codebook.

Breaking down MIMO testing

While MU-MIMO and mMIMO come with considerable benefits for link reliability, spectral efficiency, and throughput, testing this technology is a complex task especially when compared to traditional SISO systems. In basic Wi-Fi SISO setup for instance, a traffic generator sends traffic through the access point (AP) to the station (STA) or client device. Where the transmitted data from the AP is sent through a programmable attenuator to the STA to generate a traffic analysis. In a MIMO system multiple RF paths are necessary as well as a multipath emulator and bi-directional equipment for both uplink and downlink testing. That way, an RF environment can effectively be recreated reliably through conductive testing.

First, a pulsed test signal is sent to the MIMO device under test (DUT) and portions of the test signal can be transmitted from each of the DUT's antennas to one or more test antennas. Depending on the test setup, the DUT antennas can be configured to transmit uplink signals and receive combined downlink signals while the test antennas receive combined uplink signals and transmit downlink signals, or vice versa. In order to simulate real-world conditions, the test antennas are connected to a programmable RF attenuator, or RF attenuation matrix, that simulates varying distances between the DUT and test antennas (Figure 3). For a 4x4 MIMO DUT, the attenuation matrix must have at least four inputs. Naturally, this increases with 8T8R, 16T16R, 64T16R, and so on. Programmable attenuators are connected to one or more bidirectional butler matrices to combine the MIMO signals and varied in steps to measure the throughput over the path loss. Non-blocking, full fanout, bidirectional matrices can also be used to accomplish the desired attenuation profile. In order to test the effect of multipath, channel emulators can be employed in tandem with attenuator matrices to more accurately repeat a real propagation environment.

With every MIMO test system, there are slight variations that allow for minute optimizations. For instance, the passive butler matrix can be chosen due to its ability to connect devices with a dissimilar antenna count since the ports are arbitrary. However, it is one of several channel matrices. The switch matrices themselves can either come in fan-out, fan-in, or full fan-out operation. A fan-out matrix connects each input port to a limited number of outputs. In this topology, the input signal might be split via power splitters and fed to the output via a switch. The switch itself limits the number of paths to the output. However, in a full fan-out matrix all the inputs are connected with the output simultaneously. The input feed signal split and attenuated with its individual digital attenuator and combined at the output (Refer to Figure 1). Multiple paths can run these input signals simultaneously. This way, the output ports can share inputs. This provides more test flexibility in scenarios where multiple input signals may be split between arbitrary output ports and vice versa.

Multipath emulators can also leverage a variety of channel models for more accurate traffic analysis. Some iterations of Wi-Fi MIMO test provide selectable switching between a 2.4 GHz or 5 GHz butler matrix block. The options open up greatly with the different frequencies used in 5G with small-cells, millimeter-wave communications, and mMIMO along with Wi-Fi 6 and now with Wi-Fi 6E. As these systems grow in antenna count and frequency, these systems become exponentially more difficult to test accurately. Conductive testing for the many RF environments found in next-generation wireless networks is by nature varied and highly specific depending upon the use case. Reprogrammable RF devices enable engineers to build in custom test routines for a degree of flexibility that larger, proprietary systems may not allow for.

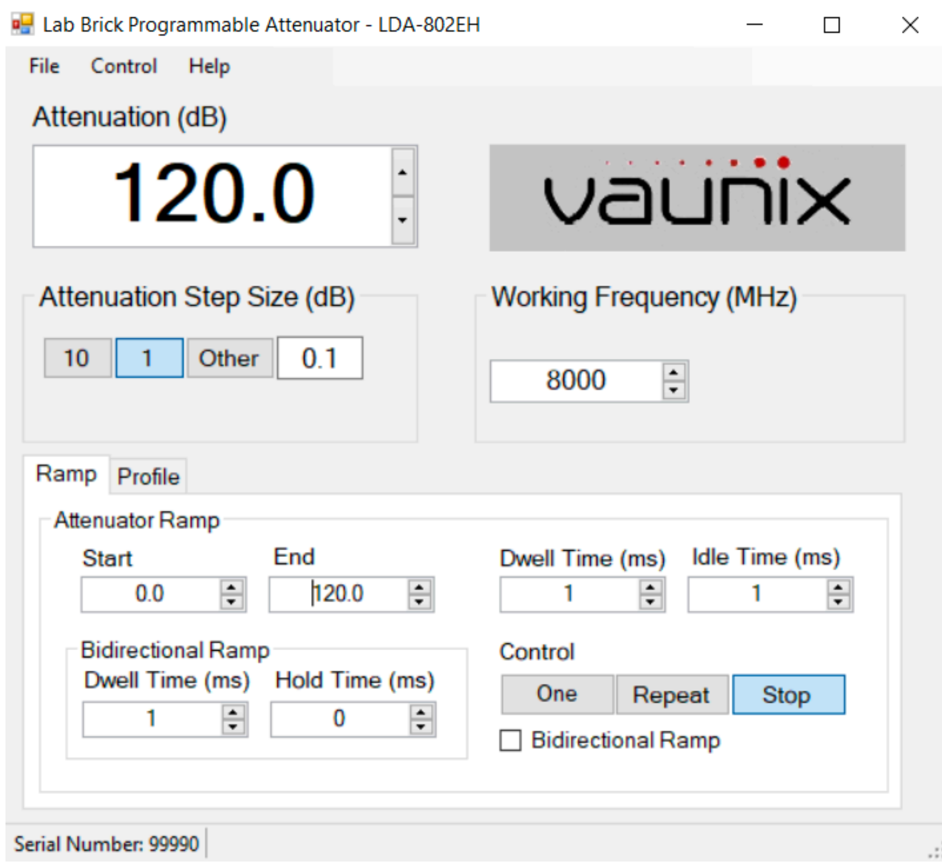


Figure 4. Vaunix lab brick digitally programmable attenuators can be easily programmed via free software.

The benefits of USB-controlled equipment

Programmable attenuators can be controlled with analog voltage adjustment, or with digital inputs with serial interfaces such as RS232 or TTL, or with GPIB. More modern units offer control using a LAN port or USB. Using ethernet or USB lowers the barriers for automated testing with the ability to use practically any PC, notebook, or laptop for control. Accessibility is a driving factor for much of the USB-based test equipment industry. These devices fill the gap that custom-proprietary standalone equipment leaves. Traditional fading simulation generally rely upon highly complex and expensive single-box testing solutions that are ultimately limited by port number, internal hardware, and proprietary software. Where most test systems rely on an OS specific to the device and cannot be easily programmed or customized, programmable RF instruments can leverage the OS of the externally connected computer to generate a custom test sequence or, free software and sample literature to program their test system. With a Vaunix USB-controlled digital attenuator, swept attenuation ramps and fading profiles are easily actualized within a user's test system directly from the included Graphical User Interface (GUI) or, with other programs such as LabVIEW, Linux, Python, and more (Figure 4). This level of reconfigurability is critical for the modern wireless testing industry that is constantly subject to new releases, evolving specifications, and changing technologies.

Key parameters to look for in programmable RF test devices

The vendor diversity for programmable RF devices such as digital attenuators to larger switched matrices is quite high. On one end, smaller units will list basic features and specifications while larger, more expensive box-type testing solutions tend to offer about the same amount of information. With the relatively limited access to data, how is a customer able to discern which system is right for their application? For these systems functionality and modularity are paramount, possibly even more so than electrical performance. Selecting a wide bandwidth system suited for the range of frequencies that will be tested is critical; not just for short-term test setups but future-proofed test systems that keep up with ongoing spectrum additions. Systems with more input and output channels as well as a full fan-out configuration can offer the flexibility necessary in current and future MIMO testing. Engineers that are required to simulate fast fading profiles for fast moving devices would require attenuators with a rapid switching speed on the order of microseconds. An adequate attenuation range might also be critical to for instance, completely block out communication between two sensitive radios. The accuracy of the applied attenuation is important in order to accurately emulate real world signal attenuation. Smaller 0.1 dB attenuation steps allow for higher resolution fading profiles. High power handling might allow a test system to better imitate the real

The language of MIMO

Key Terms	Description
Time Division Duplex (TDD)	Uplink and downlink communications are the same frequency but are separated in time.
Frequency Division Duplex (FDD)	Uplink and downlink communications are in two different frequencies but at the same time.
Channel State Information (CSI)	The information that includes the combined effect of various signal degrading occurrences (scattering, fading, NLOS, power decay, etc) as a signal moves from transmitter to receiver.
Channel Reciprocity	Normally, the CSI is estimated at the receiver and sent back to the transmitter (CSIR). In TDD systems, the physical forward and backward channels are reciprocal since they operate on the same carrier frequency. This property allows for an estimation of CSI at the transmitter (CSIT). The ability to estimate the CSI at both the receiver and transmitter due to their reciprocal, or asymetrical nature, in TDD systems is known as channel reciprocity.
Precoding	A multi-stream beamforming technique used at the base station to transmit "weighted" signals to the receiver to minimize error at the receiver output as the receiver (e.g.: cell-phones) circuitry is often simpler and may not be able to decode the signal with the same amount of processing.
Pilot Sequence	A method for quick channel estimation at the receiver by sending using the combined knowledge of the transmitted and received signal for the recovery of a channel that can be distorted or degraded with fading or scattering.
Pilot Contamination	In a set-up with multiple massive MIMO systems, the iterative use of pilot sequences in several co-channel cells generated pilot contamination, this degrades the performance of the system drastically.
CSI Codebook	A CSI acquisition methodology where a number of candidate precoding matrices are gathered in a codebook where based on its channel estimates, the user equipment can assess the optimal precoding matrix to provide more flexibility to the base station and improve performance.

Key terminology in understanding the advantages and disadvantages behind Massive MIMO technology.

signal strength during experimentation. All of these parameters are determining factors for an RF simulator, switched matrix, handover, and MIMO test systems. And, while insertion loss and VSWR are also significant considerations, these parameters are more factors that inevitably come with using passive RF components in any test system.

Outside of these parameters, configurability is key. Whether the RF device is a phase shifter, attenuator, or switch, identical adjustments made to any and all of these components should be accomplished easily via a singular platform as opposed to disjointed user interfaces (UIs). This minimizes the risk of human error in the test system and streamlines the process of generating a custom testing protocol. An intuitive UI that allows the engineer to change device settings on-the-fly lessens both the learning curve and time-to-market for end-products. Manufacturers that have individual programmable devices may not have larger test systems available or much diversity in stock. In order to prevent the purchase of extraneous system features, it is important to stick with a vendor that offers a range of devices and systems with varying levels of performance and frequency bands.

Conclusion

In the modern test environment with USB-based test equipment and programmable test devices, engineers are finding more flexibility in test configurations and programmability. This is especially true for modern handover and MIMO test systems where the frequency band, channel models, number of channels, and test parameters are often subject to change. In this dynamic testing space, modular, customizable, and reconfigurable test systems are key.

Digital attenuator handover test systems such as these provide the necessary level of reconfigurability, cost-effectiveness, and ease of control offered by modular and efficient USB-based digital attenuators.

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