Wi-Fi Channel Emulation Goes Mainstream

Craig J. Mathias, Principal, Farpoint Group
Fanny Mlinarsky, President, octoScope

Final – 5 July 07

The remarkable success of the IEEE 802.11 wireless-LAN standard [http://grouper.ieee.org/groups/802/11/], aided by the equally notable progress of the trade association founded to exploit it, the Wi-Fi Alliance [http://www.wi-fi.org/], has resulted in the broad availability of wireless LANs (WLANs) across numerous markets and applications.

Beyond the significant installed base present in residential settings worldwide, we are seeing major installations in enterprises, often involving thousands of access points, and increasing installations in metropolitan areas providing voice and data services that rival cable, DSL, and other wireless technologies designed to address the personal and business access needs of individuals.

It does not appear at this point that there is any technology that will obsolete Wi-Fi anytime soon, and we consequently expect continual proliferation of Wi-Fi across all of the above three venues. Note that this analysis ignores the embedded systems market, as well as the hundreds of millions of Wi-Fi radios that we expect to see annually built into handsets of various forms from this point forward. Considering these, the market opportunity is exceptional, to say the least.

Along with progress in the market has come a steady stream of improvements to 802.11 and their subsequent consideration in the Wi-Fi specification. While many of these have addressed such elements as security, time-bounded performance, and regulatory requirements, the most visible have been those dealing with throughput. 802.11b advanced throughput from the original one and two Mbps to 11 Mbps peak, and is largely credited with initiating the period of explosive growth in WLANs that continues to this day.

802.11a added OFDM and operation in the 5 GHz bands, and 802.11g moved the technology of .11a into the 2.4 GHz. bands of the original standard and .11b. Users have in general been able to rely on achieving throughput of at least a third of rated speed under typical operating conditions, taking into account the rate-vs.-range behavior inherent in wireless and subject to such other elements as the construction of buildings hosting indoor operations and the ever-present threat of interference from both Wi-Fi and non-Wi-Fi sources in the unlicensed bands.

Throughput can often reach on the order of half of rated, and most users have found this performance acceptable enough for WLANs to become the preferred vehicle for default and even primary access in many cases.

The ever-present rate-vs.-range problem, which also clearly impacts overall WLAN capacity, provides a continual motivation to further exploit radio technology in the quest for greater throughput, range, and capacity. The 802.11n standard is designed as the next step in addressing these elements.

Incorporating MIMO/OFDM, .11n is now far enough along in the standards-development process that the Wi-Fi Alliance has developed a specification for the interoperability testing of products conforming to the Draft 2.0 release of 802.11n. This is a very important development - since users buy Wi-Fi, and not, strictly speaking, 802.11, we expect the floodgates to open over the next few months resulting in a large array of Draft 2.0-based .11n products for both the residential and enterprise markets.

While some are cautioning that the final standard will not be issued until late 2008 or even early 2009, and may include changes creating fundamental incompatibilities with implementations based on Draft 2.0, we do not believe that such is likely, and would be regardless addressed via backwards compatibility to the current Wi-Fi Draft n specification.

It is therefore important to be in the process of developing and testing .11n products today. But this brings up a very critical question – exactly how does one go about testing wireless-LAN products with the fundamental complexity of 802.11n?

The simple answer here, of course, is to use the same test equipment as is applied to current generations of .11 products. There is, however, a key consideration inherent in this strategy, and that is the subject of this article.

Given the complex behavior of MIMO/OFDM signals interacting with the environment, some form of channel emulation is essential in providing an adequate picture of the performance likely to be realized in any given implementation of an 802.11n-based product.

MIMO and 802.11n Channel Models

Multiple-Input/Multiple-Output (MIMO) will form the basis of most[1] 802.11n implementations in the near term. MIMO is a fundamentally complex technology, but, for our purposes here, the most important element it possesses is an inherent dependence upon multipath.

Multipath, for almost all of radio history, has been a detriment to radio performance, primarily due to Rayleigh fading. The development of the RAKE receiver addressed the challenges of a multipath-rich environment to some degree, but no universal solutions appeared.

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[1] Some, particularly hand-held .11n implementations, will involve space-time block coding (STBC) and will not utilize MIMO.

MIMO, on the other hand, actually depends upon multipath – in fact, the more multipath, the better performance we see in MIMO-based systems. But as the behavior of WLANs operating in freespace is essentially impossible to characterize, the importance of channel emulation has grown over the years.

Simply put, a channel emulator is a specialized piece of electronic test equipment designed to implement a reproducible environment for the emulation of radio-wave propagation.

Channel emulators have been available for many years; examples include the Spirent SR5500 Wireless Channel Emulator [http://www.spirentcom.com/analysis/technology.cfm?az-c=pl&media=7&ws=325&ss=156] and TAS 4500 FLEX5 RF Channel Emulator, and the Elektrobit Propsim Radio Channel Emulators [http://www.propsim.com/].

A channel emulator can create a reproducible set of conditions that allows the verification of radio performance, as well as the comparative evaluation of different implementations under identical conditions. We call the latter approach "virtual benchmarking" because all testing is performed within a synthetic environment centered on traffic generation and channel emulation.

Realizing the importance of channel modeling, the IEEE 802.11n Task Group has defined a set of six channel models[2]. The IEEE 802.11n channel models (known as A through F) are a set of mathematical equations that define how a signal gets altered while traversing typical physical channels between two MIMO stations.

Model A defines an artificially small room with no multipath reflections and is included to help calibrate the channel emulator. Model B emulates reflections of a typical small room. Models C through F represent increasingly larger office spaces and outdoor settings.

Reflections and Clusters

When an RF signal propagating from the transmitter to the receiver reflects from an uneven surface, a cluster of reflections is created. A cluster consists of multiple reflections of the same signal arriving at the receiver at different times and with different amplitudes, but from the same general direction. The number of clusters represents the number of independent propagation paths in the channel.

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[2] "TGn Channel Models," V. Erceg et al, IEEE 802.11 document 11-03/0940r4

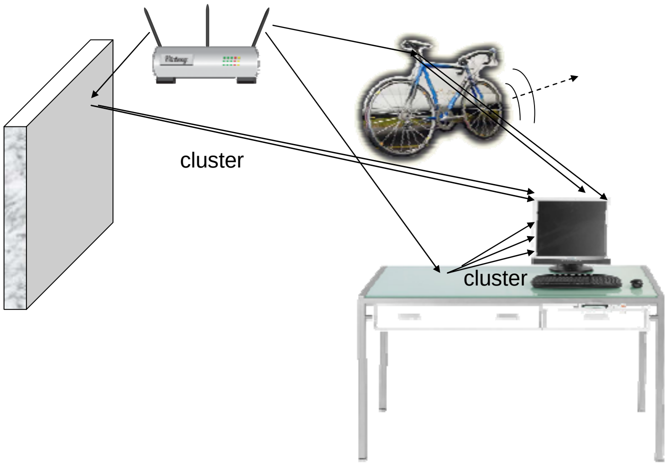

Figure 1: RF signals reflect from stationary and moving surfaces and reach the receiver in clusters. The larger the physical space being modeled, the more clusters arrive at the receiver over a longer period of time.

The larger the physical space being modeled the more clusters appear in the model and the greater the RMS (root mean square) delay spread (see Table 1). RMS delay spread is the average difference in the delay among the clusters at the receiver.

	IEEE 802.11n Models					
	A	**B**	**C**	**D**	**E**	**F**
Avg 1st Wall Distance (m)	5	5	5	10	20	30
RMS Delay Spread (ns)	0	15	30	50	100	150
Maximum Delay (ns)	0	80	200	390	730	1050
Number of Taps	1	9	14	18	18	18
Number of Clusters	N/A	2	2	3	4	6

Table 1: Key parameters of the IEEE 802.11n models A-F. Delay spread and number of clusters increase as the modeled physical space gets bigger.

Taps of a channel emulator are used to model reflections and clusters of reflections. Each tap represents a time delay and magnitude of a particular reflection in the channel (see Figure 2). Multiple taps can model a single cluster and clusters can overlap in time.

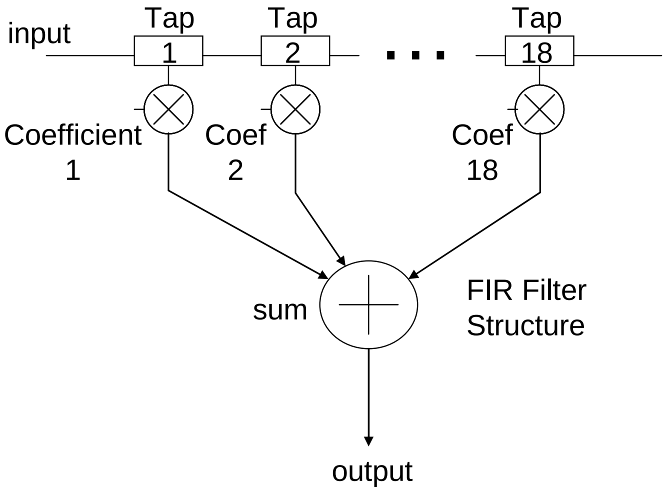

Figure 2: Key element of a channel emulator – FIR (finite impulse response) filter structure modeling the sum of multiple delayed versions of the input signal. Each successive tap introduces additional time delay to the propagating signal. At each tap a unique time-variable coefficient models the magnitude and phase of the reflection corresponding to the time at the tap.

The larger the physical space being modeled, the more taps are required in a channel emulator. The IEEE channel models D-F, emulating large spaces, require 18 taps (Table 1). The signal propagates in series through the successive taps with each tap adding equal delay to the signal.

At each tap, the signal is multiplied by the time-variable coefficient that sets the amplitude and phase of the reflection modeled by the tap. All these reflections of the original signal are summed in the adder and presented as the output and this output is the original input signal that's been computationally subjected to multipath and fading.

The time-variable nature of the coefficients enables the emulator to produce time-variable channel conditions that can emulate true to life dynamic changes in the multipath and fading environment emulating the motion of people or 11n stations.

MIMO Transmission

MIMO transmission makes use of orthogonal antenna polarization or multipath in the channel to send multiple data streams simultaneously in the same physical space – a concept called *spatial multiplexing*.

Spatial multiplexing is central to MIMO and has the potential of doubling throughput in the channel when two spatial streams are used. Spatial multiplexing requires multiple transmitters and multiple receivers. An NxM MIMO system has N transmitters and M receivers. The number of transmitters and receivers must each be greater than or equal to the number of spatial streams being transported.

The 802.11n draft specifies a maximum configuration of 4x4 MIMO, which means that the device can have up to four transmitters and four receivers. Although draft 802.11n specifies up to 4 spatial streams, current commercial chipsets can only transport two streams and are available in the 2x2, 2x3 and 3x3 MIMO configurations with the extra transmitters and receivers serving to implement TX beamforming or TX/RX diversity (see sidebar).

Sidebar: Transmit and Receive Diversity in the Draft 802.11n Standard

Transmit diversity techniques being standardized in 802.11n include *Space Time Block Coding (STBC)* and *Cyclic Shift Diversity (CSD)*. Transmit diversity improves signal reception by virtue of sending the same data stream from multiple transmitters using specialized coding (STBC) or time offset techniques (CSD) to improve reception.

Beamforming is a technique whereby a radio can use multiple transmitters to focus and direct the electromagnetic energy of the signal to the target receiver. Beamforming relies on bidirectional channel sounding between two stations and requires that the channel emulator provide bidirectional channel modeling.

Receive diversity is usually implemented via *Maximum Ratio Combining (MRC)*. MRC uses multiple MIMO receivers to acquire the same stream via uncorrelated paths through the channel thereby minimizing the destructive interference of multipath.

Typically, each receiver can hear each transmitter through unique paths in the channel. Each receiver must select and recover one of the spatial streams and tune out the other streams.

To test a receiver’s ability to select and recover the optimum stream, the channel emulator must model the possible paths from each transmitter to each receiver so as to present each receiver with what it would “hear” in the real world. Furthermore, to test the beamforming capabilities of a MIMO system, the channel emulator must model all signal paths bi-directionally.

MIMO Channel Emulation

Traditional channel emulators, such as those noted above, were originally designed to support conventional SISO (single-input/single-output) transmission used by cellular phones and base stations in such systems as GSM or CDMA. These products were later updated to support OFDM, which is used, for example, in 802.11a and .11g. SISO channel emulators provide only one FIR Filter structure between the two devices under test (see Figure 3).

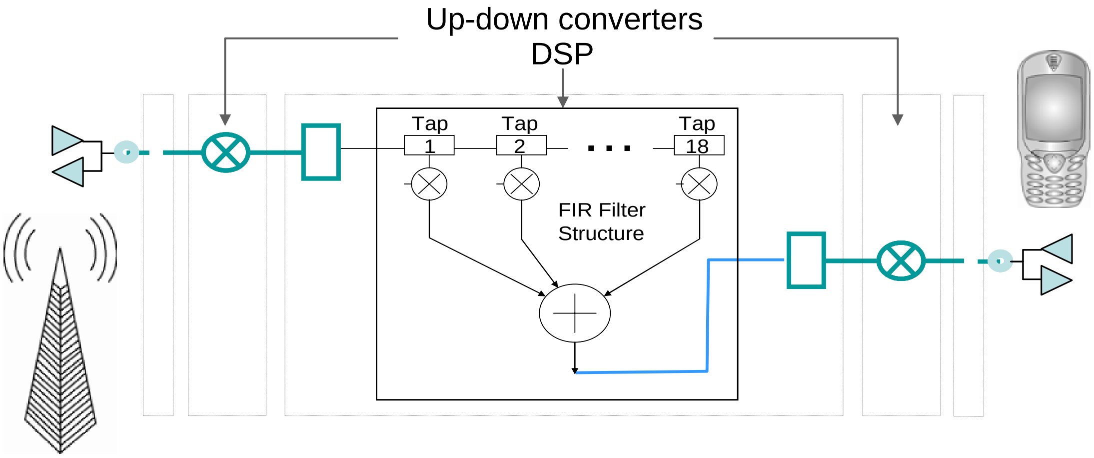

Figure 3: Traditional single-path channel emulator – the path has the structure of an FIR filter and models multipath in the channel.

While traditional channel emulators only emulate a single path, a MIMO channel emulator has to provide the FIR structures for each possible path in a MIMO channel.

The number of possible paths is N (number of transmitters) multiplied by M (number of receivers). A 4x4 MIMO system, the highest configuration specified in draft 802.11n, has 16 possible paths (4 times 4). The FIR filter coefficients on all the paths are mathematically correlated since they are modeling one physical space.

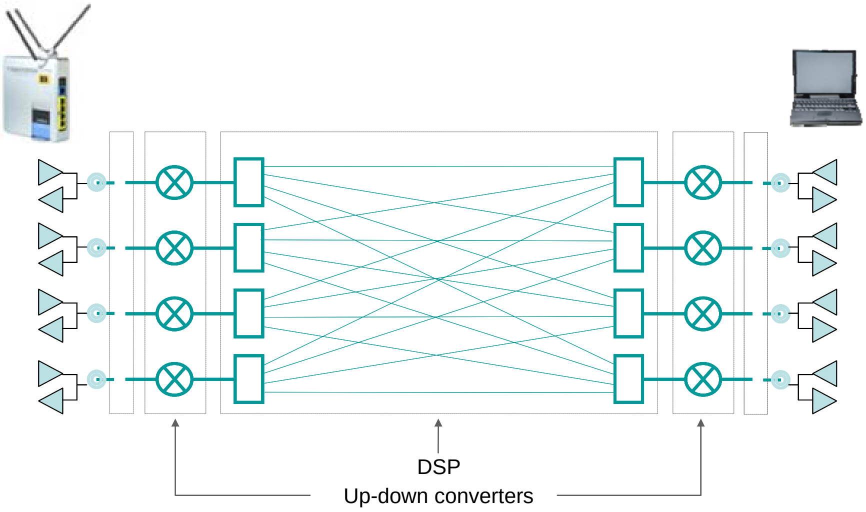

Figure 4: MIMO channel emulator block diagram. In a 4x4 emulator, 16 paths are modeled with the coupling from each transmitter to each receiver. Each path, represented here by a line, is an FIR structure shown in figure 2 emulating reflections and clusters in the channel.

A unidirectional 4x4 MIMO channel emulator thus has 16 times the complexity of a traditional SISO channel emulator. A bi-directional 4x4 MIMO channel emulator has 32 times the complexity. With 32 FIR filter structures, the MIMO channel emulator is clearly very computationally intensive, requiring a large-scale DSP engine for acceptable performance.

Antenna Modeling

The antennas of a MIMO device are modeled by the IEEE 802.11n channel models as a linear array of up to four elements with each element being a dipole antenna.

The antennas are assumed to be on a horizontal plane with equal physical distance between them. The distance between the antennas, or antenna spacing, has a significant impact on the propagation and correlation of the spatial streams and has to be specified in the channel emulator.

The wider the antenna are spaced, the more decorrelated the streams are and the higher the capacity of the MIMO channel will be. The IEEE channel models can be operated at ½, 1 and 4 wavelength spacing[3].

Doppler Shift Modeling

In real life, reflections don't come from stationary objects alone, such as furniture and walls, but also from moving reflectors, such as people or vehicles. The motion of people walking around in a typical home or office environment can result in fading of the signal. Fading is a temporary drift in signal amplitude and phase and its time characteristics depend upon the velocity of the moving object.

Fading presents a significant challenge to wireless receivers as they have to adjust to the constantly-changing phase and amplitude of the signal they are recovering. The ability to emulate fading caused by Doppler shifts is an important aspect of the IEEE 802.11n channel models.

The Doppler shifts specified by the IEEE 802.11n models assume that the reflectors are moving at 1.2 km/h (typical walking speed) with motion patterns and velocities variable in a random fashion over time.

Thus, the coefficients on the taps of the channel emulator are time-variable, constantly adjusting the magnitude and phase of the clusters in real-time. The magnitude of the fading cycles is random with a defined statistical distribution. Doppler shifts can

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[3] The wavelength of a 2.4 GHz signal is 4.9 inches (12.5 cm). The wavelength of a 5.8 GHz signal is 2 inches (5.2 cm).

attenuate the signal by as much as 40 dB, but this attenuation is frequency-selective and typically looks like notches in the frequency response of the signal.

Flat Fading

To test the receiver over a range of signal levels in addition to channel effects, some channel emulators (for example, Azimuth's ACE) also incorporate RF attenuators that provide 'flat fading' in series with the usual multipath and Doppler fading. Flat fading attenuates the entire frequency band evenly as opposed to Doppler that introduces notches in the spectrum. Flat fading has been widely used to test rate vs. range performance of RF devices through programmable RF attenuators.

Channel Emulator Dynamic Range, Noise Floor and EVM

Since a channel emulator typically employs DSP (digital signal processor) technology to model the complex and time-varying effects of multipath and Doppler shifts, the RF signal entering the emulator from the transmitter has to be down-converted to a low enough IF (intermediate frequency) for practical operation. The processed IF signal is up-converted back to its original RF frequency to be presented to the receiver (see Figure 4).

The RF subsystems performing up and down conversion must not distort the signal, which means the channel emulator's own noise floor, dynamic range and error vector magnitude (EVM) must have sufficient margin with respect to the corresponding parameters of the signal.

The A/D converter must have enough bits to handle fluctuation in the signal level at the input, and, correspondingly, the D/A converter must have sufficient resolution to handle the signal dynamic range at the output. The DSP subsystem must have sufficient resolution to handle signal fluctuations as the signal itself propagates through the FIR structures.

At the input, the RF dynamic range of the signal is determined by its PAPR (peak to average power ratio). An OFDM signal, composed of multiple carriers, fluctuates based on the phase alignment of the carriers as data pattern changes.

In draft 802.11n devices, the carriers can add constructively creating a peak power that may be up to 9 dB above the average power. At the output of the channel emulator, the dynamic range of the signal is much wider than at the input and includes PAPR plus Doppler shift that can produce down-fades as deep as -40 dB and up-fades of +3 dB (see Figure 5).

In the DSP domain, some channel emulators specify lower bit resolution at the input and higher bit resolution at the output to accommodate the wider dynamic range at the output.

For example, the Azimuth ACE specifies 12-bit resolution at the input and 16-bit resolution at the output. Inside the DSP computing engine, especially at the multipliers for the tap coefficients, the computational resolution may need to be even higher.

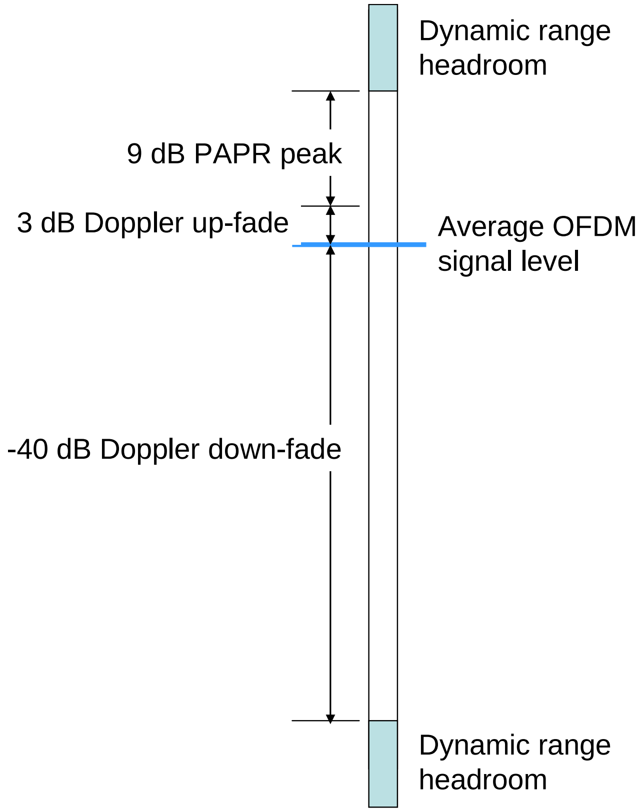

Figure 5: Requirements for the channel emulator output dynamic range – accommodate +9 dB of PAPR (peak to average power ratio) and +3/-40 dB fluctuation due to Doppler shift fading.

To prevent signal distortion, the channel emulator should have some dynamic range guardbands on the high and low ends of its dynamic range beyond the range of the signal.

It is difficult to pinpoint a single requirement for channel emulator dynamic range, since this specification varies depending on where the range is being evaluated, and whether it is in the DSP or in the RF domain.

In the RF domain, the EVM of the channel emulator over the entire dynamic range of RF subsystems should be at least 6 dB higher than EVM of the signal in order to limit deterioration of the signal EVM to less than 1 dB.

The EVM of an 802.11n signal is specified at 28 dB in the IEEE 802.11n draft but some products exceed this specification and may have an EVM as good as 30 dB. Thus the EVM of the channel emulator should exceed 36 dB across the entire dynamic range. Finally, the bandwidth of the channel emulator must support both 20 and 40 MHz channels as specified in the draft .11n standard. See Table 2 for a summary of requirements for .11n channel emulation.

Parameter	Specification	Notes
MIMO configuration	4 x 4	802.11n maximum MIMO configuration
Bidirectionality	Important	To support beamforming
Bandwidth	40 MHz	To support 20 and 40 MHz channels of 802.11n
Antenna spacing modeling	¼, 1 and 4 wave lengths, λ	λ = speed of light divided by signal frequency
Dynamic range (RF dynamic range, converter and DSP resolution)	Accommodate 52 dB of output signal dynamic range with little distortion	Signal fluctuation: +9 dB for PAPR +3 dB for up-fade -40 dB for down-fade
EVM	At least 36 dB over the entire dynamic range	To minimize distortion of a 30 dB EVM 802.11n signal

Table 2: Key requirements of a MIMO channel emulator for testing draft IEEE 802.11n products

The most important requirement for a channel emulator is handling the statistically random, time-variable nature of channel modeling that properly reflects real-world channel behavior. The channel emulator continuously sequences through randomly generated effects of reflector motion and device motion.

To be meaningful, the measurements should run for a long enough period of time to ensure that sufficient statistical variation has been incorporated into the test. Reproducibility of the test environment is, of course, always a requirement in test equipment of any form.

Conclusion

In addition to fundamental improvements in rate-vs.-range performance, we expect 802.11n to significantly improve overall reliability, especially when time-bounded traffic typical of voice, video, and multimedia is involved. And, while we have not discussed the use of 802.11n in outdoor, metro-scale deployments in this article, it is quite clear that .11n will form the basis of carrier-class implementations in this application in the future.

This brings up the question, of course, of exactly how these products will be tested as well. We believe even here that the days of freespace performance evaluation and verification are coming to an end, and that sophisticated engineering tools represent the only viable path going forward.

Realistic and comprehensive test environments are key for chip vendors, board and system builders, and, ultimately, end-users as well, introducing the possibility that today's test equipment will evolve into comprehensive tools with applications far beyond the lab and manufacturing. Channel emulation, regardless, will be a key element in all future WLAN test and performance-evaluation equipment.

Sidebar: Wi-Fi Channel Emulators

Channel emulators available on the market fall into two categories:

1 - Traditional channel emulators were originally designed to test SISO-based cellular and legacy 802.11 a/b/g systems and some have been adapted to test MIMO. This approach typically requires connecting together multiple boxes to support multi-transmitter, multi-receiver MIMO systems. The interconnections external to the boxes may be elaborate and MIMO configurations consequently tend to be costly.

2 - A new generation of purpose-built channel emulators, from the leading WLAN test equipment vendors Azimuth and Veriwave, have been designed for MIMO testing from the start.

Azimuth's ACE supports up to a 4x4 bi-directional MIMO configuration in a single box and also provides shielded enclosures for the devices under test to eliminate crosstalk and external interference thereby creating a controlled repeatable test environment.

Veriwave's WaveBlade incorporates a .11n channel emulator that works with the company's traffic generator/analyzer and supports all of the IEEE channel models.