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Test Strategies for 802.11n MIMO Devices

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Executive summary

True to the trend of ever-increasing data rates, the new IEEE 802.11n WLAN (Wireless LAN) transmission technology based on MIMO (Multiple Inputs/Multiple Outputs) guarantees throughput of at least 100 Mbps but can deliver up to 600 Mbps depending on the complexity of the 802.11n radio and on the environment.

MIMO is a highly innovative advancement in wireless data transmission. It turns the long-time nemesis of wireless – multipath – into a friend. Multipath is a common occurrence indoors where the wireless signal reflects from surfaces thus creating multiple signals that add together in the air. While today's 802.11 a/b/g radios struggle to separate the original signal from this muddle, the MIMO radio actually takes advantage of multipath to send multiple data streams via the available paths.

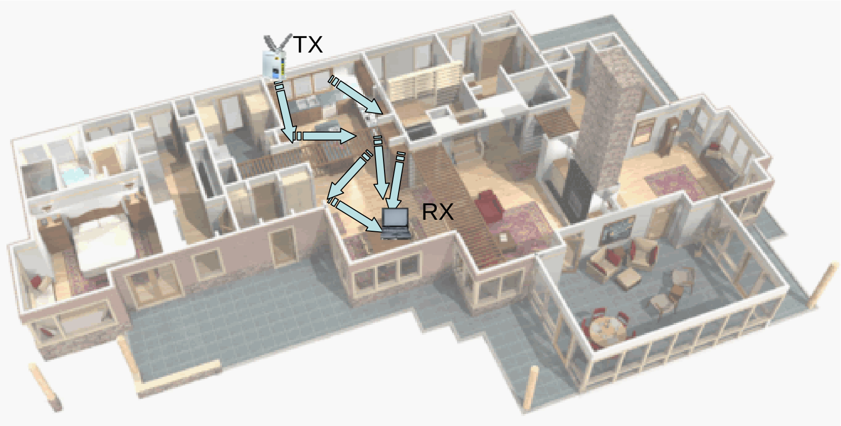


Figure 1: Multipath creates multiple versions of the signal by virtue of reflections from walls, floors, ceilings, furniture and people. The reflections add together in the air presenting a challenge to the receiver of separating out the original signal. Until now multipath was a problem that limited operating range. Now MIMO radios actually use multipath to achieve gains in operating range.

A MIMO NxM system typically refers to N transmitters and M receivers.

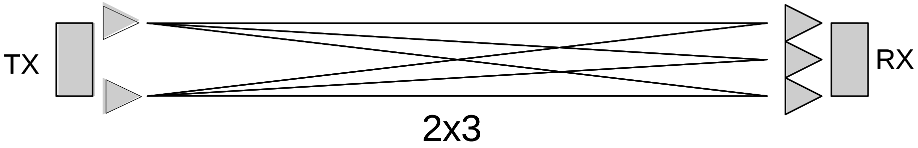


Figure 2: An example of a 2x3 MIMO system with 2 transmitters and 3 receivers.

Key elements of 802.11n specification and anticipated products

The IEEE 802.11n standard deals with two flavors of MIMO – **Spatial Multiplexing** and **Beamforming**. Spatial Multiplexing splits up a data streams into multiple lower data rate streams and sends these data streams simultaneously via multiple paths in a multi-path channel. These multiple unique streams are re-combined in the receiver to form the original stream of higher data rate. Beamforming sends multiple versions of same data stream to improve reception. Beamforming can also work in conjunction with a technique called Maximum Ratio Combining (MRC). MRC is a DSP technique that adjusts amplitudes and phases of received data signals and adds them in such a way as to optimize the Bit Error Rate (BER) performance.

Backwards compatible MIMO devices can operate in 3 modes: Legacy (802.11a,b,g), Mixed mode (802.11n and 802.11a,b,g) or Green Field (802.11n only). The highest throughput is achieved in Green Field mode when only the 802.11n devices are present on the network. The mode of operation impacts network throughput and at this stage of the MIMO evolution it is important to compare the throughput performance of Legacy, Mixed and Green Field modes. A single legacy station on a MIMO network can significantly slow down the total network throughput.

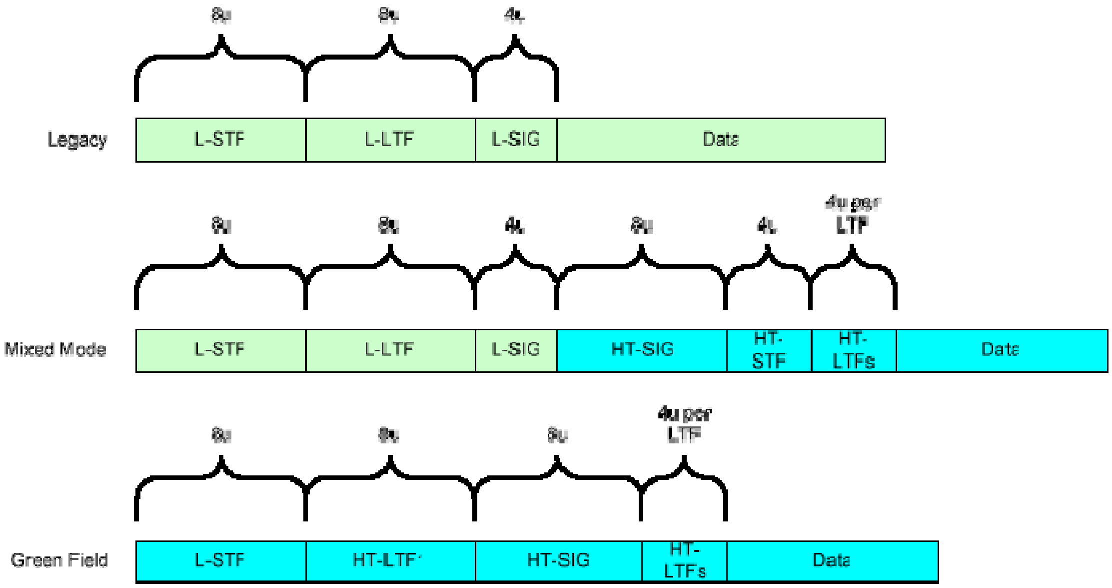
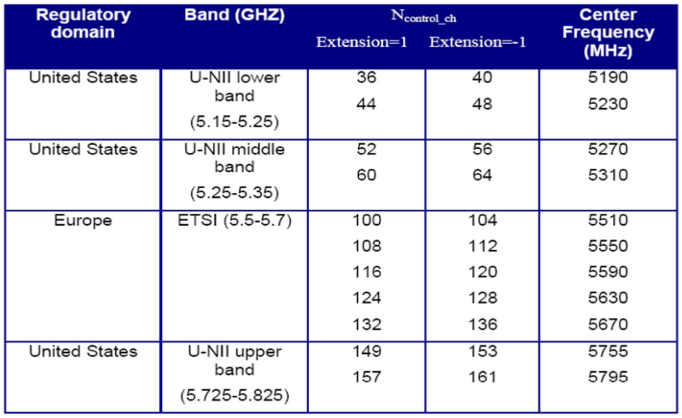


Figure 3: The PLCP (PHY Layer Convergence Protocol) Frame Formats include L-STF: Legacy Short Training Field; L-LTF: Legacy Long Training Field; L-SIG: Legacy Signal Field; HT-SIG: High Throughput Signal Field; HT-STF: High Throughput Short Training Field; HT-LTF: High Throughput Long Training Field; HT-LTF's: Additional High Throughput Long Training Fields; Data – The data field includes the PSDU (PHY Sub-layer Data Unit)

Green Field 802.11n networks are composed entirely of MIMO devices and can run at PHY transmission rates of up to 600Mbps. Green Field networks can, therefore, support bandwidth-hungry applications such as transmission of multiple HDTV streams for video distribution in the home.

For handhelds, 802.11n has the potential of improving battery life by minimizing the time required to send and receive data packets and through the use of improved power saving techniques.

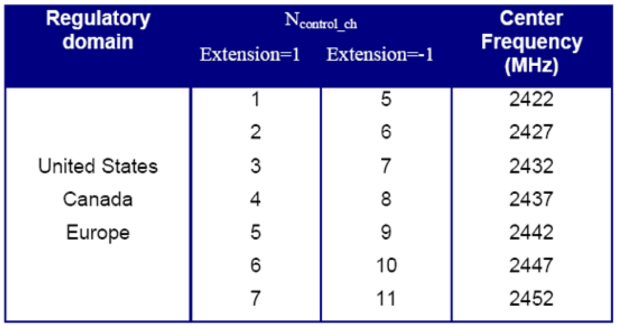
802.11n networks use existing unlicensed bands at 2.4GHz and 5GHz matching the frequency plan of legacy networks. While the legacy 802.11 networks use 20 and 25MHz channels, 802.11n networks can use 20 or 40MHz channels.



Regulatory domain	Band (GHZ)	$N_{control\_ch}$		Center Frequency (MHz)
		Extension=1	Extension=-1	
United States	U-NII lower band (5.15-5.25)	36	40	5190
		44	48	5230
United States	U-NII middle band (5.25-5.35)	52	56	5270
		60	64	5310
Europe	ETSI (5.5-5.7)	100	104	5510
		108	112	5550
		116	120	5590
		124	128	5630
		132	136	5670
United States	U-NII upper band (5.725-5.825)	149	153	5755
		157	161	5795

Channel center frequency = (5000 + 5*n) MHz, where n=0..200

Figure 4: 40MHz Channel Allocation in the 5GHz Band



Regulatory domain	$N_{control\_ch}$		Center Frequency (MHz)
	Extension=1	Extension=-1	
United States Canada Europe	1	5	2422
	2	6	2427
	3	7	2432
	4	8	2437
	5	9	2442
	6	10	2447
	7	11	2452

Channel center frequency = (2407 + 5*n) MHz, where n=1..11

Figure 5: 40MHz Channel Allocation in the 2.4GHz Band

Modulation Coding Schemes

While legacy 802.11a,b,g networks use single-stream DSSS or OFDM modulation across the data rates, 802.11 MIMO networks introduce a concept of Modulation Coding Scheme (MSC) that incorporate 8 variables to implement rate adaptation.

Existing standards:

- 11b (DSSS-CCK) – 1, 2, 5.5, 11 Mbps in 2.4 GHz band

- 11a (OFDM) – 6, 9, 12, 18, 24, 36, 48, 54 Mbps in 5 GHz band
- 11g – both 11b and 11a rates in 2.4 GHz band

For 802.11n MIMO, each data rate may employ a different modulation scheme defined by the MSC. Each MCS is determined by a set of parameters:

- Modulation
- Coding rate
- Number of spatial streams
- Number of FEC encoders

To make matters even more interesting, multiple MCSs may have the same PHY rate. Radios establishing a link must automatically negotiate the optimum MSC based on channel conditions and must automatically adjust the selection of MSC based on motion of devices or changing channel conditions caused by fading and other real-time events.

There are 77 different MCSs specified in the current draft[1] with 8 of them being mandatory for 802.11n-compliant devices to implement. Here's an example of how MCSs are specified in the IEEE draft.

Rate dependent parameters for mandatory 20 MHz, N_{SS} =1 modes. N_{ES} = 1.

MCS Index	Modulation	R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mbps)	
								800ns GI	400ns GI[1]
0	BPSK	½	1	52	4	52	26	6.5	7.2
1	QPSK	½	2	52	4	104	52	13.0	14.4
2	QPSK	¾	2	52	4	104	78	19.5	21.7
3	16-QAM	½	4	52	4	208	104	26.0	28.9
4	16-QAM	¾	4	52	4	208	156	39.0	43.3
5	64-QAM	2/3	6	52	4	312	208	52.0	57.8
6	64-QAM	¾	6	52	4	312	234	58.5	65.0
7	64-QAM	5/6	6	52	4	312	260	65.0	72.2

Table 1: Example: 8 mandatory 20 MHz channel MSCs in the current IEEE 802.11n draft. The draft goes on to specify 77 different MCSs for 20 and 40 MHz channels with a variety of spatial streams and other conditions:

Symbol	*Explanation*
N_{SS}	*Number of spatial streams*
R	*Code rate*
N_{BPSC}	*Number of coded bits per single carrier*
N_{SD}	*Number of data subcarriers*
N_{SP}	*Number of pilot subcarriers*
N_{CBPS}	*Number of coded bits per symbol*
N_{DBPS}	*Number of data bits per symbol*
N_{ES}	*Number of FEC encoders*

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[1] IEEE P802.11n/D1.0, March 2006

With 77 MSCs to choose from, the complexity of rate adaptation decisions becomes considerably higher than in legacy networks. This level of complexity is likely to make interoperability between devices from different vendors challenging. Presently the testing of early MIMO devices suggests that interoperability between different implementations is an issue[2]. Interoperability may continue to be an issue unless the standard is simplified.

MIMO channel models

Since multipath environment is inherent to making MIMO work, the throughput performance of MIMO networks and selection of MCSs are highly dependent on the physical space.

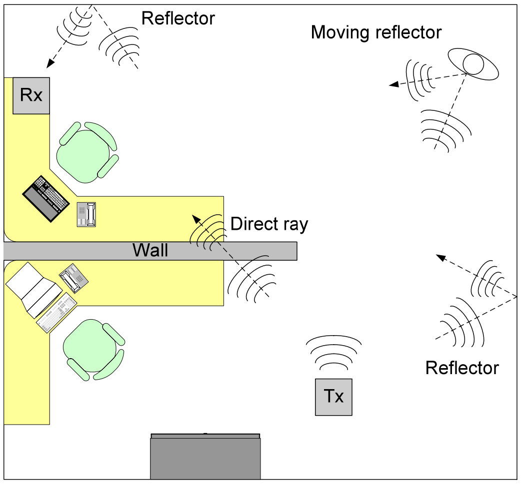

Figure 6: Radio signals reflect from walls, furniture and other conductive surfaces, which causes the receiver to 'see' multiple clusters of the same signal arriving at different times and with different amplitudes. In this figure we see 3 or 4 major clusters.

Multipath reflections come in "clusters". Each cluster is caused by a specific group of reflectors. Reflections in a cluster arrive at a receiver from the same general direction. Following an extensive analysis of cluster statistics, the IEEE 802.11n group defined 6 channel models[3] –A through F. Model A is a test mode. Model B represents a typical small office environment. Model F represents large metropolitan spaces.

IEEE models A-F are defined in the form of tapped delay lines or FIR (Finite Impulse Response) filters. These models assume linear antenna arrays for transmitters and receivers with ½, 1 and 4 wavelength element spacing.

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[2] See "Draft 802.11n Revealed: Part 1 - The Real Story on Throughput vs. Range" by Tim Higgins at http://www.tomsnetworking.com/2006/06/01/draft_11n_revealed_part1/index.html

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

Since each model defines some particular representative environment (e.g. a typical floor of an office building) the multiple signal paths are correlated based on the model of the physical space.

The models include Doppler shifts, which are amplitude fluctuation of signals at the receiver. The fluctuations are caused by moving objects that reflect RF propagation – people, cars, etc. The Doppler shifts are modeled assuming reflectors are moving at 1.2 km/h, which corresponds to about 6 Hz in the 5 GHz band and 3 Hz in 2.4 GHz band.

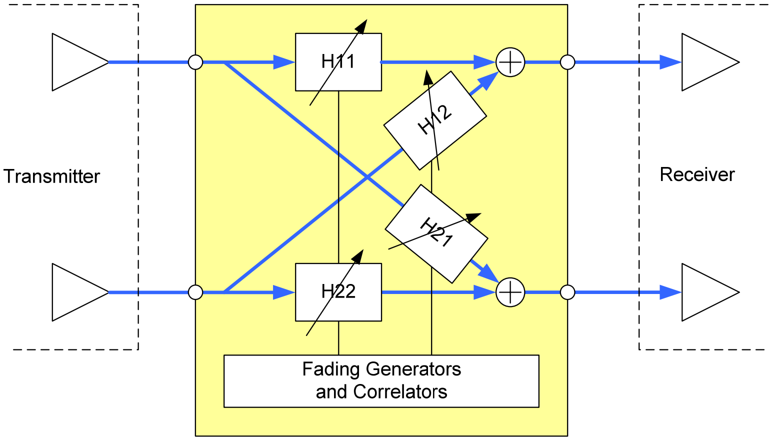

Figure 7: Time-varying FIR filter weights are spatially correlated: H11 correlated with H12, etc., according to antenna spacing and cluster statistics. The coefficients are also time correlated according to the Doppler model.

Delay spread and the number of clusters vary based on the size of the modeled environment. The number of clusters represents number of independent propagation paths modeled.

	Models					
Parameters	**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

Figure 8: Key parameters in the IEEE 802.11n models A-F. Delay spread and number of clusters increase as the modeled physical space gets bigger. The number of taps also increases as a function of physical size to provide sufficient resolution of the emulation.

Measuring range performance through a channel emulator

When measuring MIMO range performance and comparing performance of different products, two methods can be used: with channel emulation or in bypass mode.

When measured with channel emulation, the testing should be done using the IEEE 802.11n models, which are the only standards-based universally accepted models of representative physical settings. The IEEE channel models are an objective means of comparing the range performance of competing MIMO products.

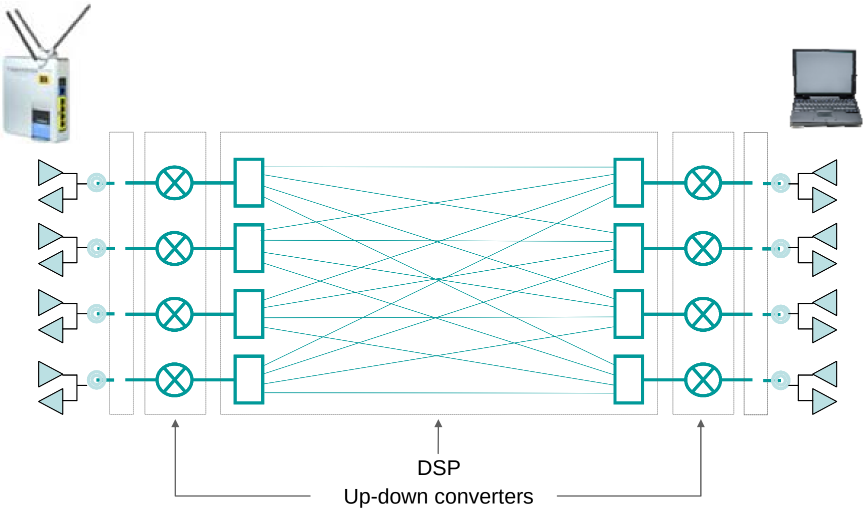

Figure 9: MIMO channel emulator block diagram. In a 4x4 emulator, 16 paths (n^2) are modeled with the coupling from each transmitter to each receiver. The 16 paths must be modeled bidirectionally so that the same exact channel effects are applied to signals injected from either port.

Channel emulation must be bidirectional since the Beamforming method requires channel sounding. The signal traveling from one port of the emulator to the other must go through the same exact channel as the signal going in the return direction. The transmitter may derive channel information from the ACK frames sent by the receiver and use this information to select the optimum MCS for transmission. Other channel sounding methods are also being explored by the IEEE 802.11n committee, but bidirectionality is required for any of these methods.

The MSCs support up to 4 MIMO streams. Therefore, the channel emulator should offer a 4x4 configuration. A typical channel emulator down-converts the inbound RF signal to a lower IF frequency. It then digitizes the signal and implements the IEEE models using Digital Signal Processing (DSP). The IF signal processed by the DSP is up-converted and presented to the station at the opposite port.

Each MIMO receiver in the radio has to train on one of the transmit signals. In spatial multiplexing each transmit stream must be received since the transmit streams carry different data to be combined into a single stream at the receiver. In the case of Beamforming, the streams carry the same data, so Maximum Ratio Combining (MRC) of multiple streams can be used by the MIMO receivers.

The fastest theoretical throughput is achieved in the bypass mode of the emulator when each of the MIMO receivers is presented with a single optimum quality data stream. A single data stream means less work for the receiver DSP – no need to extract the stream from of the sum of several streams caused by multipath. Bypass mode results in optimum throughput since each receiver gets a clean signal and therefore performs at the highest possible BER (bit error rate).

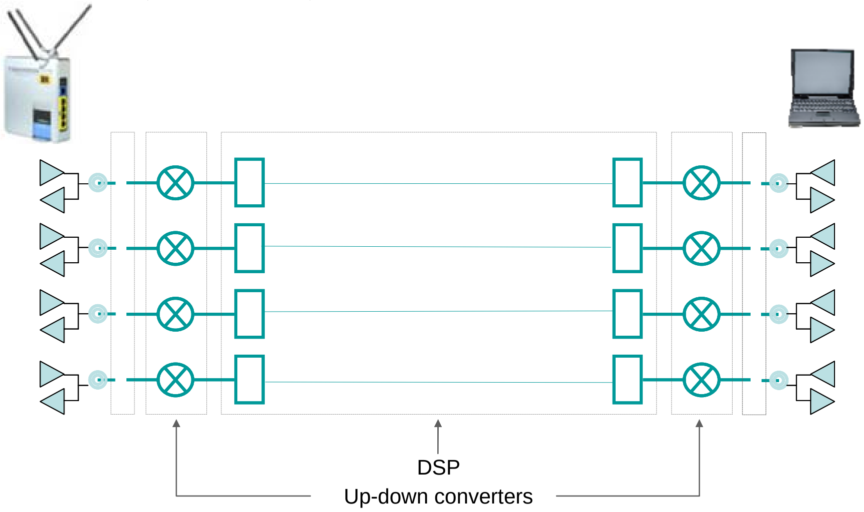

Figure 10: Bypass mode of the channel emulator results in the maximum theoretical throughput since each receiver is fed a single clean data stream with no coupling from adjacent transmitters.

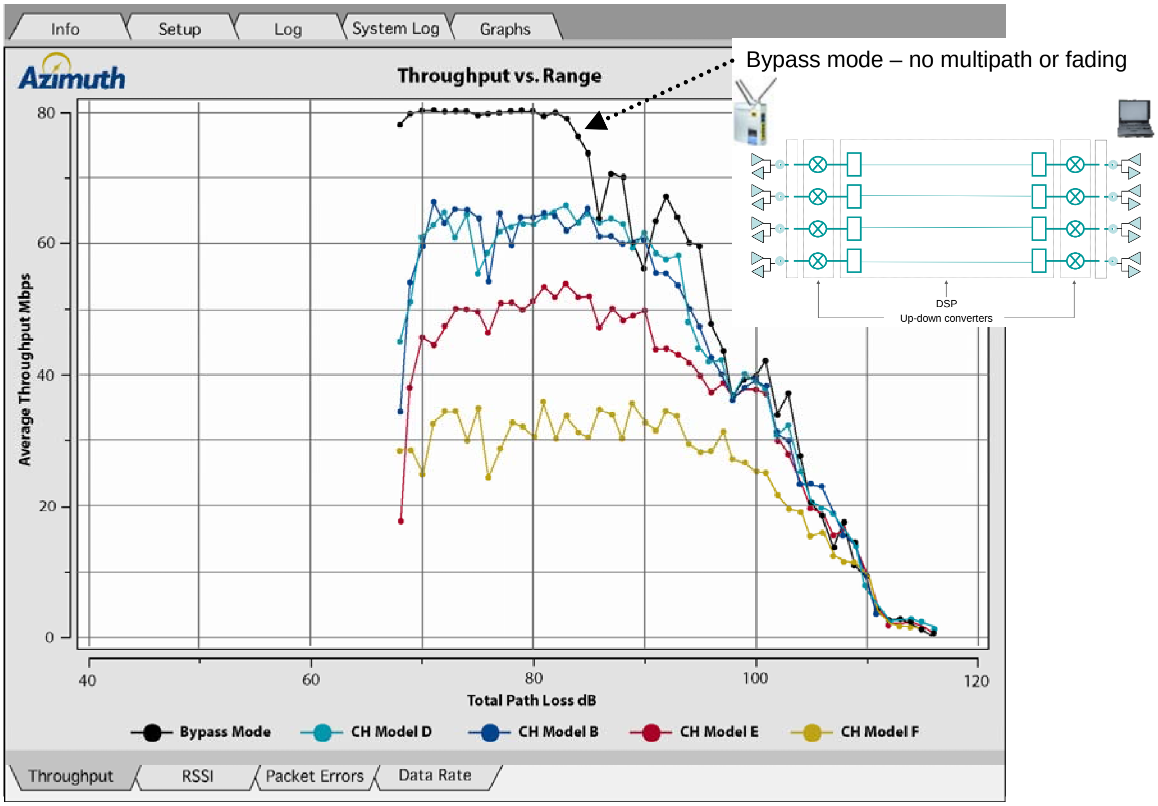

Figure 11: Throughput measurement using the Azimuth ACE channel emulator. Throughput varies as a function of path loss and as a function of the selected channel model. The highest throughput is achieved in bypass mode.

When a channel emulator is not available, MIMO devices can be tested in bypass mode by cabling each transmitter to each receiver directly through programmable attenuators with coaxial cables.

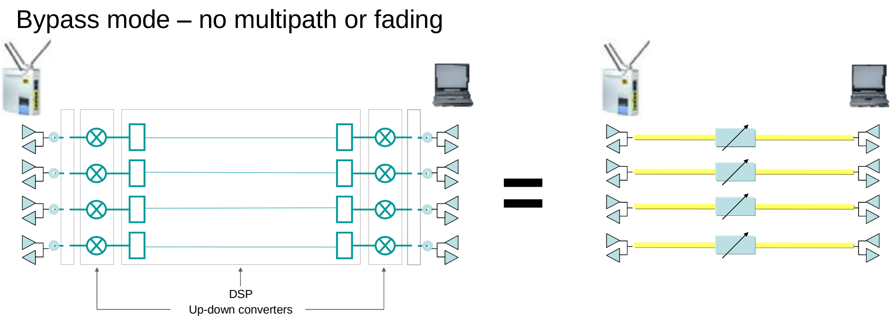

Figure 12: Bypass mode can be configured either through a channel emulator or by cabling receivers and transmitters directly through programmable attenuators.

While bypass mode does not exercise the ability of MIMO radios to lock onto the best signal or to optimally combine received signals, it is an accurate metric of maximum theoretical throughput performance of the radios. Bypass mode can be used to test interoperability of devices and to compare maximum throughput of devices in a controlled and repeatable manner.

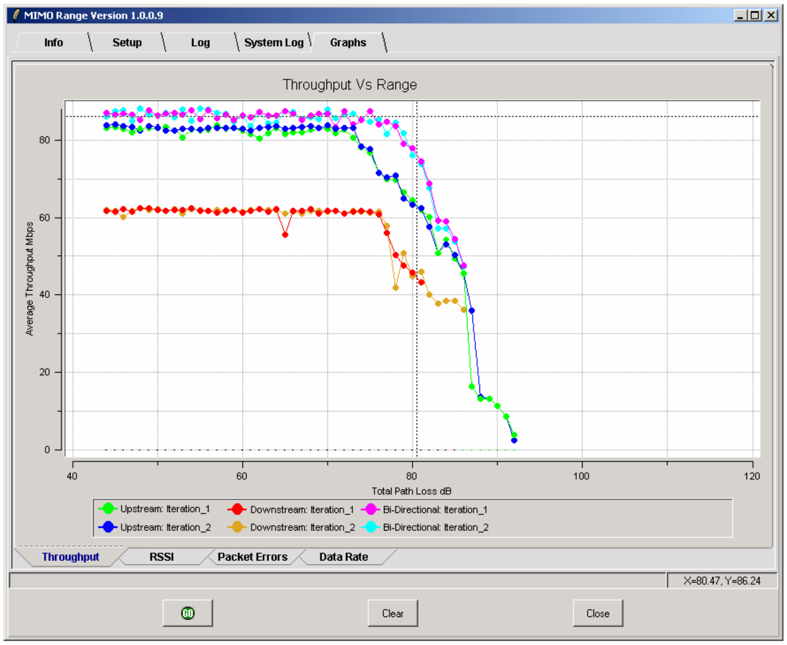

Figure 13: Throughput measurements in bypass mode performed on the Azimuth 800W system.

Bypass mode is well-suited to measuring the throughput of simple MIMO networks to compare performance differences between Mixed Mode networks, where legacy devices may be present, and Green Field networks, where only the MIMO devices are present.

Bypass mode can also be used to measure roaming performance where a station's motion can be emulated between 2 APs using programmable attenuators.

Controlled conducted test environment

To achieve repeatable test results, devices under test must be shielded from one another and from external interference. The testing specification being developed by the IEEE 802.11T committee defines conducted test environment as being composed of shielded enclosures that contain devices in the test setup being interconnected with shielded cables through a network of RF attenuators, combiners and switches.

In a conducted environment for testing throughput performance, the devices under test – station and AP – can be enclosed into the Azimuth Radio Proof Enclosures (RPEs) that offer not just shielding but filtering on every conducted connection (e.g. Ethernet) to the DUTs.

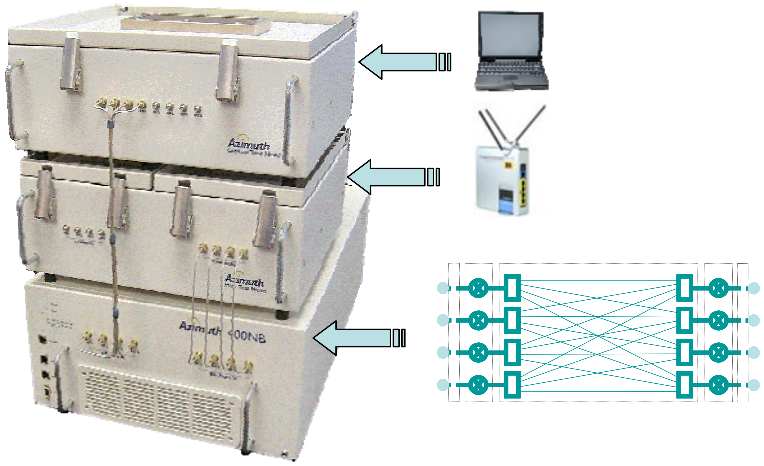

Figure14: Controlled conducted test environment for range performance testing of MIMO devices. A MIMO client PC is housed in the Azimuth RPE-401, a MIMO AP is housed in the Azimuth RPE-402 and both devices are connected via RF cables to the Azimuth Channel Emulator (ACE). In this environment external interference and crosstalk between the DUTs are strictly controlled.

Preventing interference between devices under test is crucial when measuring range performance. With radio sensitivity of 802.11 devices extending down to -80 or -90 dBm, even if antennas are removed and devices cabled to a channel emulator effective shielding and filtering techniques are required to control the crosstalk between devices. Without proper enclosures, the crosstalk typically overpowers the low level signal and limits the range of the measurement to 40 dB or less, which leaves the low end of the 80-90 dB dynamic range of the radios untested. This defeats the purpose of the test since most radios work just fine at high receive levels and only begin to differ in performance at the more challenging low levels. To measure the problematic low end of the dynamic range performance, RF enclosures should provide device isolation that exceeds the dynamic range of the radios. This typically requires not just shielding but also sophisticated filtering of all conducted lines going through the test heads to the DUTs.

Basic tests

The initial basic tests of new MIMO devices include range and throughput performance as well as roaming performance. These tests should include throughput measurements in Legacy, Mixed and Green field network modes.

Comparison of performance in these three modes and interoperability testing are best performed in the bypass mode through programmable attenuators.

Range performance testing focusing on the radio should be performed using a channel emulator. Basic tests aiming to compare the throughput performance in different modes can use the Azimuth chassis with RFMs.

	Test setup	***Test environment***	***Azimuth equipment***
Range performance with channel emulation	1 station, 1 AP	Conducted environment connected through a 4x4 bidirectional channel emulator	ACE Channel Emulator; MIMO Radio Proof Enclosures (RPEs)
Range performance in bypass mode	1 station, 1 AP	Conducted environment connected through variable attenuators	800W or 300W chassis; RF port Modules (RFMs); MIMO RPEs
Throughput performance in Legacy mode	2-stations 1 AP; both stations in Legacy mode (802.11a,b,g)	Conducted environment connected through variable attenuators	800W or 300W chassis; RFMs, MIMO RPEs
Throughput performance in Mixed mode	1 station in Legacy mode, 1 station in MIMO mode, 1 AP in MIMO mode	Conducted environment connected through variable attenuators	800W or 300W chassis; RFMs, MIMO RPEs
Throughput performance in Green Field mode	2 stations in MIMO mode, AP in MIMO mode	Conducted environment connected through variable attenuators	800W or 300W chassis; RFMs, MIMO RPEs
Roaming test	2 MIMO APs; 1 MIMO station	Conducted environment connected through variable attenuators	800W or 300W chassis; RFMs, MIMO RPEs

Table 2: Basic tests for the emerging MIMO devices

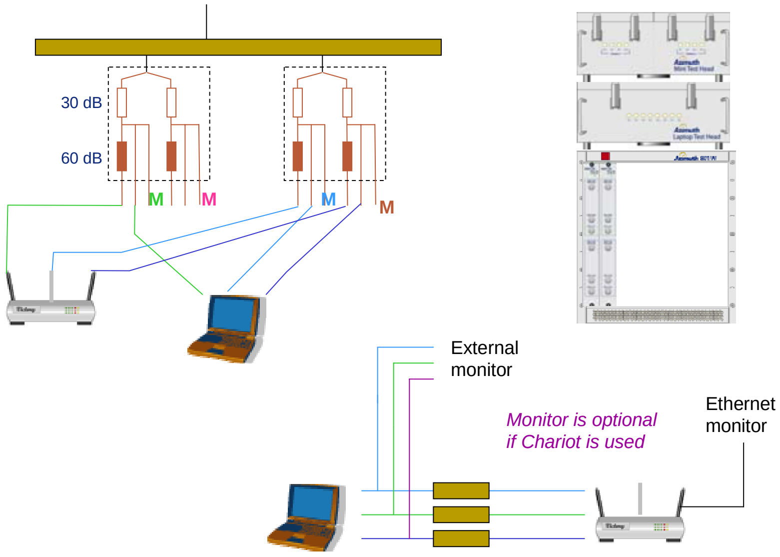

Figure 15: Range test in bypass mode using the Azimuth 800W chassis and RPEs

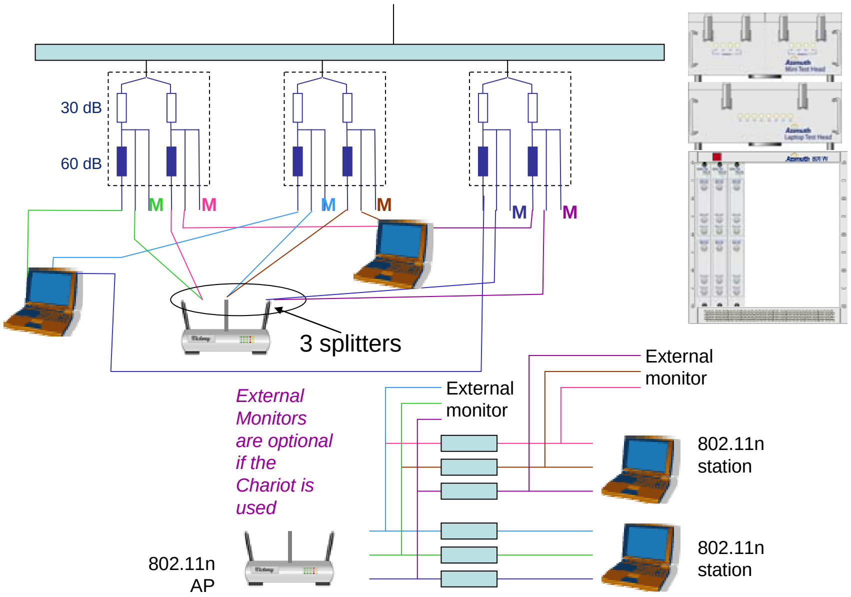

Figure 16: 2-station 1 AP Greenfield network throughput test using the Azimuth 800W chassis and RPEs

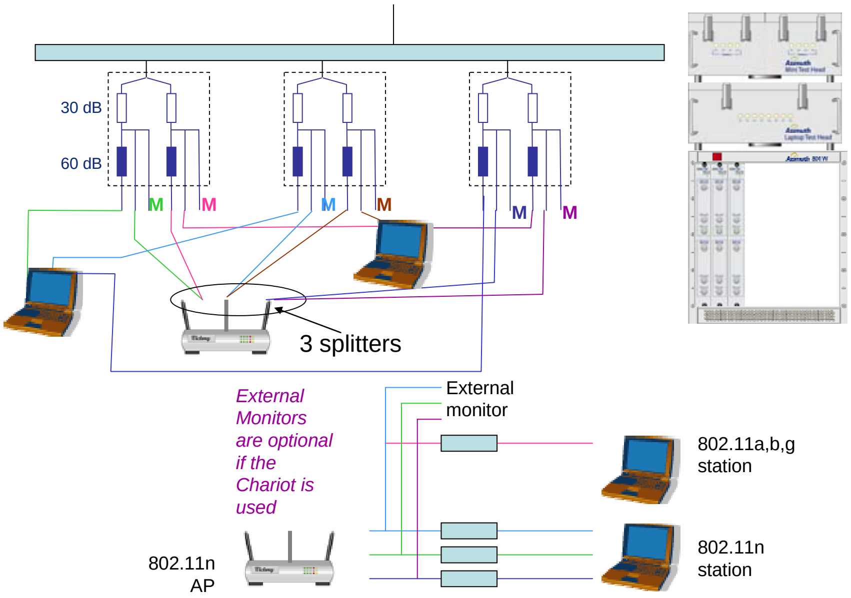

Figure 17: 2-station 1 AP Mixed mode network throughput using Azimuth 800W chassis and RPEs

Roaming tests can also be performed in bypass mode using the Azimuth chassis with RFMs.

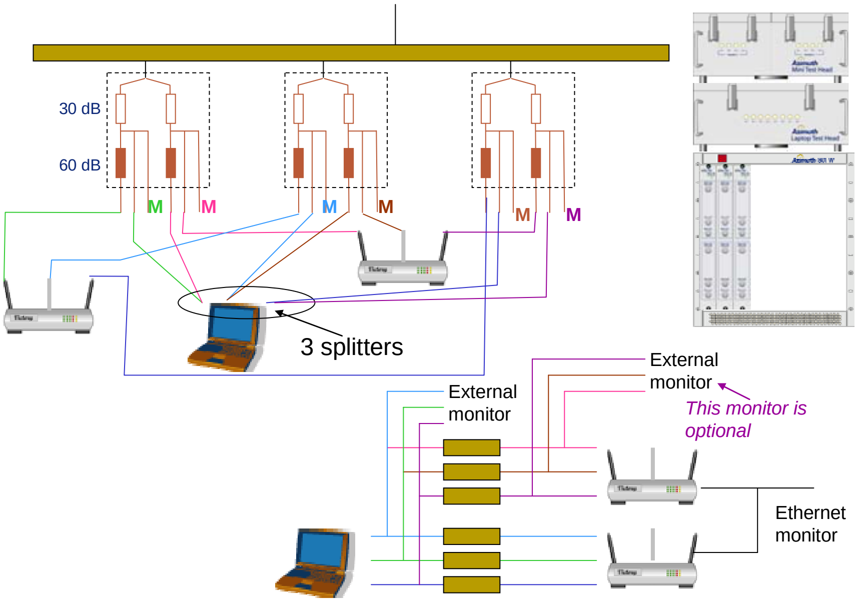

Figure 18: 2-AP 1 station roaming test using the Azimuth 800W chassis and RPEs.

Figure 19: Azimuth 300W chassis and RPE-based conducted test setup for MIMO interoperability and throughput testing. Devices under test are enclosed in MIMO RPEs and connected through RFMs in the chassis.

Summary

As new 802.11n MIMO devices are arriving on the market, the industry must assure the robustness and interoperability of these devices before they are deployed. A few basic throughput, interoperability and roaming tests described here are bound to uncover significant issues in the early implementations and help vendors fix these issues before products are shipped.