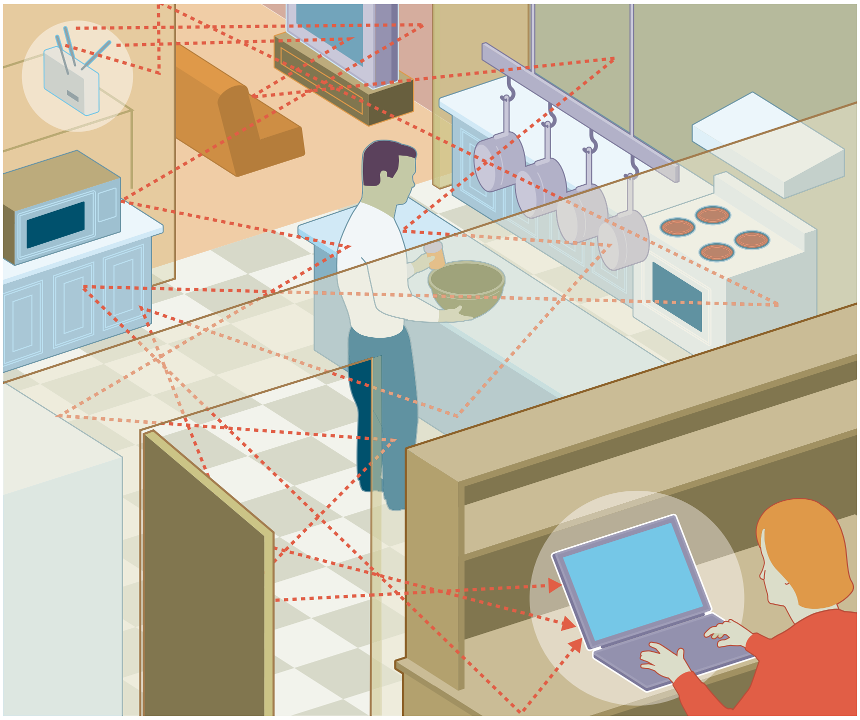

DANIEL GUIDERA

Equipment meeting the complex 600-Mbps multiple-input, multiple-output WLAN standard will require sophisticated channel-emulation test strategies.

Testing 802.11n

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Wireless LAN (WLAN) throughput advancements introduced by the emerging IEEE 802.11n standard come at the price of unprecedented technological complexity. This creates an immediate need for sophisticated test systems that can help manufacturers and service providers bring robust, well-tested products to market. Although the final standard will not be published until mid-2009, draft 2.0 is now mature enough that companies such as Intel, Broadcom, Atheros, Marvell, and Qualcomm have already released 802.11n chipsets that will require only software changes in order to comply with the final standard.

IEEE 802.11n will be able to reach data rates of 600 Mbps, and it guarantees a minimum of 100 Mbps of throughput (see "Throughput and packets," p. 42). Throughput is not just a function of data rate and can be adversely affected by protocol overhead and retransmissions caused by poor signal integrity.

Throughput measurements for legacy 802.11a,b,g networks often take place over the air link where overhead counts toward throughput, but 802.11n specifies throughput at the MAC SAP (Media Access Control Service Access Point) interface, where the metric more meaningfully reflects true data throughput. A throughput of 100-Mbps at the MAC SAP interface for 802.11n represents a fourfold increase over the throughput of legacy WLAN technology.

Prestandard 802.11n solutions claim data rates in the 300-Mbps range—the level at which access points (APs) need Gigabit Ethernet connections to the infrastructure to keep up with the air link. IEEE 802.11n owes its high throughput to the latest advancement in wireless transmission—MIMO (multiple input, multiple output).

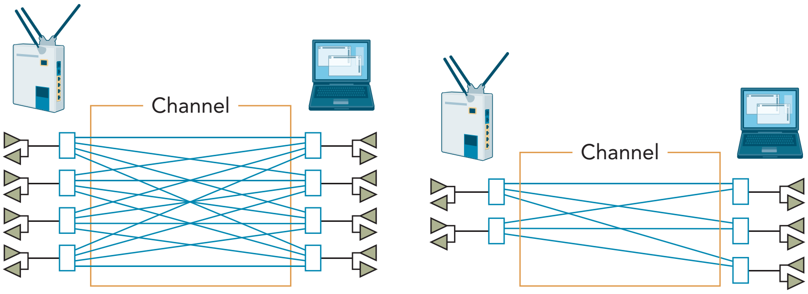


FIGURE 1. 802.11n specifies MIMO operation with up to four transmitters and four receivers. Some products feature two transmitters and three receivers, and some have three transmitters and three receivers with other combinations possible.

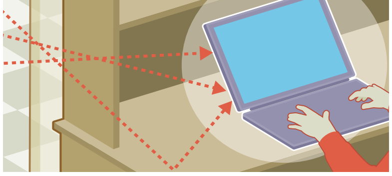


Table 1. Prestandard implementations and manufacturers' claims

Prestandard chipset	Claimed throughput* (Mbps)	Number of transmitters, receivers, spatial streams, and antennas supported (*N*x*M*: *N* transmitters, *M* receivers)
Atheros AR5008-2NG	150–180	3x3, 2 streams**
Broadcom Intensi-fi	180–200	2x2, 2 streams
Intel 4965AGN		2x3, 2 streams
Marvell TopDog		2x3, 2 streams
Qualcomm/Airgo AGN400	170–175	2x3, 2 streams

**These throughput figures are reported by the manufacturers, and the measurement methodology may not be available. For reliable throughput metrics and comparison, the measurements should be performed by an independent party using a controlled test environment specified in the IEEE 802.11T test specification.*

***The Atheros chipset has more transmitters than streams to implement cyclic shift diversity (CSD), a signal-shaping technique incorporated into the 802.11n specification. CSD spreads the spatial streams across multiple antennas by transmitting the same signal with different cyclic shifts.*

How does MIMO work?

MIMO is a true innovation in the area of wireless data transmission. It turns the long-time enemy of airborne signals—multipath—into a friend. Multipath is a common phenomenon in wireless channels, where the signal reflects from walls, furniture, and people. Reflections add together in the air, causing the signal at the receiver to be a distorted version of the original. While 802.11a,b,g radios work to overcome the effects of multipath, 802.11n MIMO radios actually take advantage of multiple paths to increase throughput by sending several data streams simultaneously. This requires multiple transmitters and receivers in the radio.

An *N*x*M* MIMO system has *N* transmitters and *M* receivers (**Figure 1**). Signals from each transmitter reach each receiver via a different path in the channel. MIMO works best if these paths are spatially distinct and each is capable of carrying its own data stream. If the radios are within line of sight of each other, MIMO can deteriorate into the traditional single-stream transmission, SISO (single input, single output).

The 802.11n standard incorporates two MIMO techniques: spatial multiplexing and beamforming. Spatial multiplexing divides data into multiple streams and sends them simultaneously over multiple paths in the channel. These streams are recombined in the receiver to get the original data.

Table 2. Legacy 802.11 physical-layer data-rate adaptation and frequency band

	Supported data rates (Mbps)	Frequency band (GHz)
802.11b (DSSS)	1, 2, 5.5, 11	2.4
802.11a (OFDM)	6, 9, 12, 18, 24, 36, 48, 54	5.8
802.11g (combination of 11b and 11a)	1, 2, 6, 9, 12, 18, 24, 36, 48, 54	2.4

Beamforming is a technique that uses several directional antenna elements to spatially shape the emitted electromagnetic wave to beam the energy into the receiver over some optimum path. Beamforming requires the transmitting and receiving stations to perform channel sounding to optimize the shape and direction of the beam.

Beamforming can be used in conjunction with spatial multiplexing or by itself when only a single path is available between the radios. Beamforming at the transmitter can be augmented with Maximum Ratio Combining (MRC) at the receiver—a technique that phase-aligns and adds signals received by multiple antennas to optimize signal integrity.

Most existing prestandard 802.11n chipsets support two spatial streams but can use more than two transmitters and receivers to shape and transport these streams. Multiple antennas or antenna elements can also be used for beamforming or for diversity. (Diversity is a technique of using two or more antennas for reception of the signal. Some diversity algorithms select the best signal from multiple antennas, and some algorithms may combine the signals.) **Table 1** summarizes how the prestandard solutions work.

Physical layer signaling for 802.11n vs. legacy

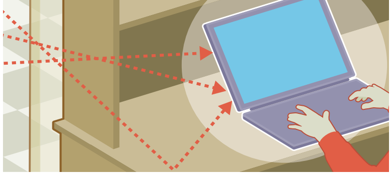
In the earlier versions of 802.11, rate adaptation seemed complex compared to single-rate Ethernet, but now it seems simple compared to 802.11n. Legacy 802.11a,b,g devices can automatically and dynamically adapt data rate based on channel conditions—the better the channel, the higher the rate. Legacy radios transmit a single data stream using either direct-sequence spread-spectrum (DSSS) or orthogonal-frequency-division multiplexing (OFDM) modulation. Data rates are automatically selected by the legacy networks (**Table 2**).

The complexity of 802.11n rate adaptation has given birth to the concept of Modulation Coding Scheme (MCS). MCS includes variables such as the number of spatial streams, modulation, and the data rate on each stream. Radios establishing and maintaining a link must automatically negotiate the optimum MCS based on channel conditions and then continuously adjust the selection of MCS as conditions change due to interference, motion, fading, and other events.

There are 77 MCSs specified in the current IEEE P802.11n draft (January 2007), with eight of them being mandatory for 802.11n compliance. **Table 3** shows an example of how MCSs are specified. The highest data rate of 600 Mbps is achievable with MCS 31 using 64-QAM modulation in a 40-MHz channel, four spatial streams, and operating with a short guard interval (GI) of 400 ns.

MIMO channel models

MIMO throughput, number of spatial streams, selection of MCSs, and beamforming techniques are highly dependent on the physical channel. To help develop and test MIMO products, the IEEE 802.11n group defined six MIMO channel models—A through F (**Table 4**). Model A is a test mode. Model B represents a typical small office environment.



Model F represents a large metropolitan environment.

Radio signals reflecting from buildings, walls, furniture, and other conductive surfaces travel in *clusters*—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. The MIMO channel models include Doppler shifts, which are amplitude fluctuations of signals caused by moving objects, such as people and cars. The Doppler shifts are modeled assuming reflectors are moving at 1.2 km/h.

Measuring range performance through a channel emulator

Throughput and range performance of 802.11n devices can be measured using a channel emulator (**Figure 2**) that implements IEEE 802.11n models. The Azimuth Systems' ACE is one such product. Channel emulation must be bidirectional to support the channel-sounding techniques used in beamforming. The transmitter may derive channel information from the ACK frames sent by the receiver or by the sounding matrix computed and reported by the receiver.

The channel emulator should offer a 4x4 configuration, since 802.11n supports up to four spatial streams. A typical channel emulator downconverts the inbound RF signal to a lower IF frequency, digitizes the signal, and mathematically applies the IEEE 802.11n models to the signal using digital signal processing (DSP), thus emulating the channel effects. The computationally distorted IF signal is then upconverted and presented to the station at the opposite port of the emulator

Backward-compatible MIMO devices can operate in three modes: legacy (802.11a,b,g), mixed-mode (802.11n and 802.11a,b,g), or greenfield (802.11n only). The highest throughput is achieved in greenfield mode when only the 802.11n devices are present on the network. A single legacy station on a MIMO network can significantly slow down the total network throughput. When measuring throughput, the operating mode will make a difference in the results and should be taken into account.

Table 4. Key parameters in the IEEE 802.11n models A–F

	IEEE 802.11n models A	B	C	D	E	F
Average 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

Note: Delay spread and number of clusters increase as the modeled physical space gets bigger.

Source: "TGn Channel Models," Vinko Erceg, et al., IEEE 802.11 document 11-03/0940r4. users.ece.utexas.edu/~forenza/11-03-0940-04-000n-tgn-channel-models.doc.

Table 3. MCSs that are mandatory in the current IEEE P802.11n draft.

MCS Index	Modulation	R	$N_{BPSC(iSS)}$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mbps) 800 ns GI*	Data rate (Mbps) 400 ns GI
0	BPSK	1/2	1	108	6	108	54	13.5	15.0
1	QPSK	1/2	2	108	6	216	108	27.0	30.0
2	QPSK	3/4	2	108	6	216	162	40.5	45.0
3	16-QAM	1/2	4	108	6	432	216	54.0	60.0
4	16-QAM	3/4	4	108	6	432	324	81.0	90.0
5	64-QAM	2/3	6	108	6	648	432	108.0	120.0
6	64-QAM	3/4	6	108	6	648	486	121.5	135.0
7	64-QAM	5/6	6	108	6	648	540	135.0	150.0

**Guard Interval (GI) is the time delay used by the receiver to let the reflections in the channel settle before sampling data bits.*

Legend

N_{SS}	Number of spatial streams
R	Code rate
N_{BPSC}	Number of coded bits per single carrier
$N_{BPSC(iSS)}$	Number of coded bits per single carrier for each spatial stream, iSS
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
N_{TBPS}	Number of total bits per subcarrier

Note: These are rate-dependent parameters for mandatory 20-MHz, N_{SS} =1 MCS, N_{ES} = 1. The draft goes on to specify 77 different MCSs for 20- and 40-MHz channels.

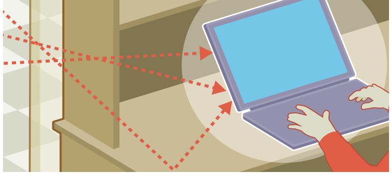
802.11n considerations for handsets

For handsets, the biggest concern is battery life. To that end, 802.11n has introduced a power-save protocol called PSMP (power save multi-poll) that enables the station to go to sleep when not transmitting or receiving. This mode is particularly valuable for VoIP devices because voice traffic has a cyclical pattern and is composed of short frames, less than 100 μs, with long periods of silence, on the order of 20 to 30 ms, depending on the codec. This traffic pattern results in a low duty cycle of radio on/off, and if the station can sleep during the off cycle, battery life can be significantly extended.

PSMP enables handsets to wake up periodically to exchange packets with the AP, powering up the radio only when necessary. PSMP is a sophisticated protocol that requires the AP to keep track of sleeping stations and to save their data for periodic delivery during the wake/sleep cycle. 802.11n also improves power efficiency through higher data rates that minimize radio ON time.

Channel frequency selection and management

The planned 802.11n networks use the conventional unlicensed bands at 2.4 GHz and 5 GHz, but while 802.11a,b,g



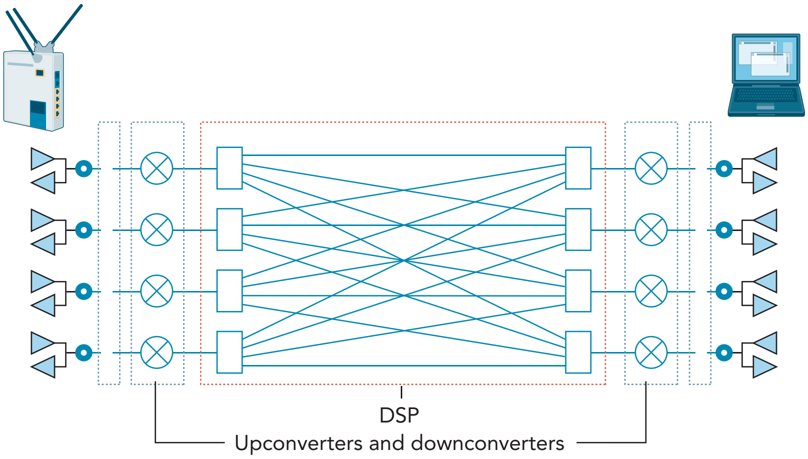


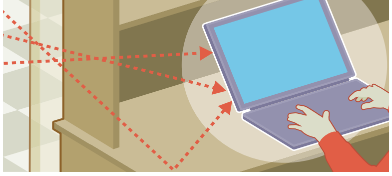
FIGURE 2. **This block diagram illustrates a MIMO channel emulator. In a 4x4 emulator, 16 paths (N^2) are modeled with the coupling from each transmitter to each receiver.**

networks occupy 20-MHz channels, 802.11n networks can use 20- or 40-MHz channels. A 40-MHz channel consists of two adjacent 20-MHz channels—primary and secondary.

Since only 70 MHz is available in the 2.4-GHz band that is already crowded with 802.11b,g networks, 40-MHz operation of 802.11n can disrupt existing networks. The issue of 40-MHz operation in the 2.4-GHz band has been a contentious one at the IEEE, and the 802.11 working group addressed it at its January 2007 meeting by introducing new coexistence protocols.

Coexistence includes methodology for detecting WLAN activity in the band, for sharing the secondary channel with adjacent Basic Service Sets (BSS is analogous to a cell in the cellular networks and consists of the AP and its associated stations), and for switching channels when necessary to avoid interference. Coexistence protocols are complex protocols requiring coordinated periodic scanning of all available channels, and the 802.11 working group may still have concerns about them—concerns that might delay the standard. Coexistence is less of a concern in the 5-GHz band where more spectrum is available. Nevertheless, the new coexistence protocols will apply to all bands of operation.

The 802.11n standard will also use the 3.65-GHz to 3.70-GHz contention-based band recently made available by the FCC and now being standardized by the IEEE



802.11y task group. This specification is expected to be published in April 2008.

Test considerations for 802.11n

As new MIMO devices arrive on the market, the industry must ensure their reliability and interoperability before they can be deployed on a wide scale. Since the biggest promise of 802.11n is increased throughput and range, the first test priority is to measure a product's throughput vs. range. This test should be performed following the conducted environment methodology specified in the IEEE 802.11T test specification and using a MIMO channel emulator, since throughput depends on a radio's ability to handle multipath signals.

Throughput and packets

Throughput is a function of packet size—the longer the packets, the higher the throughput. The shorter the packets, the more effect packet headers and interpacket gaps have on throughput.

The industry likes to specify throughput using the maximum packet size, and 802.11n has increased the maximum packet size through aggregation techniques in order to achieve the increase in throughput over legacy networks. IEEE 802.11n's 100-Mbps minimum throughput is specified using the maximum packet size.

Additional test solutions are needed to verify the many new specifications in the PHY and MAC layers. Partly due to technical requirements and partly because too many cooks share the kitchen (about 100 people actively work on the standard), 802.11n is vastly more complicated than 802.11a or 802.11g, and it includes changes to both the MAC and the PHY layers.

With an increased variety of platforms now supporting WiFi and looking to upgrade to MIMO, the IEEE 802.11 committee had to address multiple contending requirements. For example, the requirement for higher throughput may in some cases be in conflict with the requirement for power conservation and backward compatibility. With so many different requirements, the emerging standard now has many options for basic operation such as beamforming, MCS selection, greenfield mode, and coexistence. The MIMO industry needs sophisticated test solutions that will ensure successful deployments and happy users. T&MW

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