COVER STORY |

The Next Generation

As next generation wireless applications emerge, higher WLAN data throughput will be required to meet expectations of performance. | By James Michael Wilson

GLOSSARY OF ACRONYMS

802.11 TGn - IEEE 802.11 Task Group N
ACK - Acknowledgment
ADC - Analog-to-Digital Converter
AFE - Analog Front End
BAR - Block ACK Request
BSS - Basic Service Set
DSP - Digital Signal Processing
FEC - Forward Error Correction
IEEE-SA - Institute of Electrical and Electronics Engineers - Standards Association
LOS - Line of Sight
MAC - Medium Access Controller
MCS - Modulation Coding Schemes
MIMO - Multiple-Input Multiple-Output
MPDU - MAC Protocol Data Unit
MRD - Marketing Requirements Document
OFDM - Orthogonal Frequency Division Multiplexing
OTA - Over The Air
PHY - Physical
PPDU - Physical Protocol Data Unit
QAM - Quadrature Amplitude Modulation
SAP - Service Access Point
SDM - Spatial Division Multiplexing
SNR - Signal-to-Noise Ratio
TX/RX - Transmit/Receive
VoIP - Voice over Internet Protocol
Wi-Fi - short for Wireless Fidelity, a name applied by the Wi-Fi Alliance and usually taken to mean any type of 802.11 network
WLAN - Wireless Local Area Network

Illustration by Roy Scott

In response to growing market demand for higher-performance WLANs, the IEEE-SA approved the creation of 802.11 TGn in 2003. The scope of TGn's objective is to define modifications to the PHY and MAC layers that deliver a minimum of 100 Mb/s throughput at the MAC SAP (see Figure 1). This minimum throughput requirement represents an approximate four-fold increase in WLAN throughput performance compared to today's 802.11a/g networks. TGn's purpose for this next step in WLAN performance is to improve the users experience with existing WLAN applications while enabling new applications and market segments. At the same time, TGn expects a smooth adoption transition by requiring backward compatibility with existing IEEE 802.11a/b/g legacy solutions.

Wireless LAN Throughput by IEEE Standard

The Wi-Fi Alliance has also shown interest in TGn's work toward 802.11n. Industry representatives have come together under the Wi-Fi Alliance — High Throughput Marketing Task Group to define and publish an MRD. The Wi-Fi Alliance MRD specifies performance expectations that will enhance the end user's experience in regard to increased throughput, increased range, more robustness to interference, and a more reliable user experience throughout the BSS.

Achieving Next Generation WLAN Performance

Simply demonstrating 100 Mb/s under some conditions will not be enough to ensure a robust user experience with emerging applications. The next generation wireless LAN standard represented by 802.11n will need to robustly achieve and exceed the IEEE TGn target goal of 100 Mb/s at the MAC SAP. 802.11n. WLAN technology will be expected to support consumer electronics, personal computing and handheld communications platforms throughout all major enterprise, home, and public hot-spot environments. This broad scope advocates practical and cost-effective implementations that will scale robustly from low-end devices to high-throughput applications using technical approaches that may be developed and implemented within the time frames outlined in IEEE TGn.

Many in the industry believe 802.11n should use an evolutionary philosophy, reusing existing technologies where practical and, at the same time, employing as much new technology as possible. The objective is to maximize the advancement of wireless LAN in a practical manner, keeping cost minimal without complicating backward compatibility. Reuse of legacy technologies like OFDM and FEC coding, interleaving, and QAM mapping should be maintained to keep cost down and ease backward compatibility. PPDU packets should be decodable without prior knowledge of transmission method. This is to say, legacy devices must be able to decode and disposition new high-throughput packets, even if these packets are not intelligible to legacy devices.

Three key areas need to be considered when addressing increases in WLAN performance. First, improvements in radio technology are needed to increase the physical transfer rate. Second, new mechanisms implementing the effective management of enhanced PHY performance modes must be developed. Third, improvements in data transfer efficiency are required to reduce the performance impacts of PHY headers and radio turnaround delays that would otherwise mitigate the improvements achieved with physical transfer rate. At the same time, while developing new approaches in achieving performance, coexistence with existing 802.11a/b/g legacy devices is required. All of these areas must be addressed when considering practical and effective implementations for cost-sensitive markets.

Increasing the Physical Transfer Rate

When considering technical approaches that may increase the physical transfer rate, it is useful to consider Shannon's capacity equation: $C = B \log_2 (1 + \mathrm{SNR})$. This equation reflects theoretical capacity limits C when considering occupied band-

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width B and SNR at the receiver. This equation, however, is based on assumptions about the type of noise present in the wireless channel and assumes conditions such as flat fading that may not be perfectly representative of real-life wireless channels. For example, impairments such as multipath fading in real wireless channels actually represent important opportunities for increasing the overall performance of the PHY layer transfer rate.

One important approach uses multiple antenna systems for both the transmitter and the receiver. This technology is referred to as MIMO or *smart antenna* systems. MIMO exploits the use of multiple signals transmitted into the wireless medium and multiple signals received from the wireless medium to improve wireless performance. MIMO can provide many benefits, all derived from the ability to process spatially different signals simultaneously. Two important benefits explored here are antenna diversity and spatial multiplexing. Using multiple antennas, MIMO technology offers the ability to coherently resolve information from multiple signal paths using spatially separated receive antennas. Multipath signals are the reflected signals arriving at the receiver some time after the original or LOS signal is received. Multipath is typically perceived as interference degrading a receiver's ability to recover the intelligent information. MIMO enables an opportunity to spatially resolve multipath signals, providing spatial diversity gain that positively contributes to a receiver's ability to recover the intelligent information. Another valuable opportunity MIMO technology may provide is SDM. SDM spatially multiplexes multiple independent parallel data streams, transferred simultaneously within one spectral channel of bandwidth. MIMO SDM can significantly increase data throughput as the number of resolved spatial data streams is increased. Each spatial stream requires its own TX/RX antenna pair at each end of the transmission (see Figure 2). MIMO technology requires a separate AFE and ADC for each MIMO antenna.

MIMO technology will play an important role in achieving the IEEE TGn goals, and 802.11n should use this technology to evolve the existing OFDM physical interface presently implemented with legacy 802.11a/g. However, practical solutions will require additional technological approaches. Implementations requiring more than two RF antenna chains will need to be carefully architected to keep the cost low while attempting to achieve expected performance.

Baseline MIMO Configuration

Another important tool that can increase the PHY transfer rate is wider bandwidth spectral channels. Increasing channel bandwidth is not a new concept. It can easily be seen from Shannon's equation that bandwidth has a direct effect on wireless channel capacity. Using a wider channel bandwidth with OFDM offers significant advantages when maximizing performance. Wider bandwidth channels are cost-effective and easily accomplished with moderate increases in DSP. If proper-

Table1. Comparison of Different 802.11 Transfer Rates

IEEE WLAN Standards	OTA Estimates	MAC-SAP Estimates
802.11b	11 Mbps	5 Mbps
802.11g	54 Mbps	25 Mbps (when .11b is not present)
802.11a	54 Mbps	25 Mbps
802.11n	200+ Mbps	100 Mbps

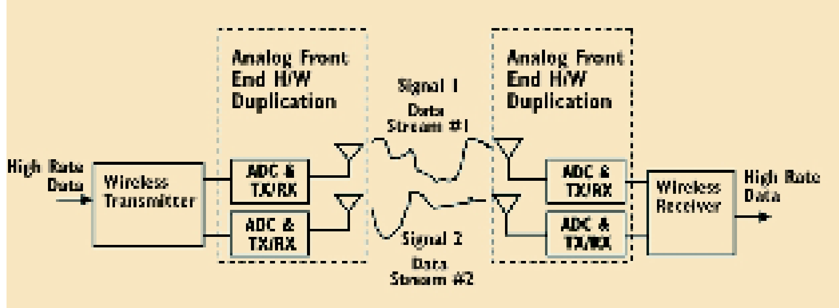

Figure 2. Basic 2x2 antenna MIMO system with two-stream SDM example.

ly implemented, doubling the legacy bandwidth of 802.11 20 MHz channels can provide greater than two times the usable channel bandwidth. Coupling MIMO architecture with wider bandwidth channels offers the opportunity of powerful, yet cost-effective, approaches for increasing the physical transfer rate.

MIMO approaches using only 20 MHz channels will require higher implementation cost to meet the TGn requirement of 100 Mb/s at the MAC SAP. Meeting the IEEE TGn requirement under most conditions with only 20 MHz channels would require at least three antenna AFEs spatially multiplexing three independent parallel data streams. Due to more demanding SNR requirements, a 20 MHz approach may struggle to provide a robust experience with higher throughput demanding applications in real user environments.

Figure 3 compares the performance of a two-antenna transmitter communicating with a two-antenna receiver over a 40 MHz channel (2x2–40 MHz) with two different 20 MHz configurations (2x2–20 MHz and with 2x3–20 MHz implementations). The primary advantage provided by a 2x3–20 MHz implementation over the 2x2–20 MHz implementation is spatial diversity gain, providing improved SNR. This simulation (using TGn channel model D) reflects over-the-air throughput at different SNR values. A MAC efficiency of 70% is assumed, and SNR is post-detection after channel impairments have been taken into account. The dashed lines on the 20 MHz channels represent a 400 ns guard interval with 7/8 puncturing of the K7 convolution code. This data shows a MIMO two-stream implementation does not achieve 100 Mb/s at the MAC SAP. Achieving the 100 Mb/s goal using only 20 MHz channels would require MIMO implementations supporting at least three data streams. It is easy to see the advantage of a 2x2–40 MHz implementation, using 800 ns guard interval with 3/4 coding, in these simulations. Using 40 MHz channels allows for reduced complexity, keeping the cost low while delivering throughput for a robust user experience.

Using both MIMO technology and wider-bandwidth channels will reliably satisfy the higher throughput demands of consumer electronics applications. This will become increasingly true as BSS environments need to service multiple high-throughput applications simultaneously. Choosing conservative increases in channel bandwidth, combined with conservative approaches in MIMO technology, will enable cost-effective solutions that meet the high demands of these emerging applications. This combined approach, using MIMO technology with 40 MHz channels, will enable 802.11n to reach even higher performance as demands for wireless content grow.

Notice how Figure 3 shows that 2x2–20 MHz implementations have trouble reaching the 100 Mb/s top-of-MAC (140 Mb/s OTA) requirement, and this is accomplished only at SNR values not practical in real user environments. The 2x2–40 MHz implementation is able to comfortably achieve 100 Mb/s top-of-MAC at a reasonable SNR.

802.11n should provide for a lowest common capability to ensure high-throughput networks function efficiently. The standard should support both 20 MHz and 40 MHz channels, where 40 MHz would be the widest channel consisting of two adjacent legacy 20 MHz spectral channels. All 802.11n devices are likely to support 40 MHz channels, where government and regulatory rules allow, as this would enable the most effective market implementation. Supporting 802.11n with all 40 MHz devices would provide the greatest possible performance within an 802.11n network, limiting inefficiencies associated with channel-width multiplexing between 20 MHz and 40 MHz devices.

Consumers in geographies where regulations permit 40 MHz operation thus would benefit from the availability of inexpensive high-throughput solutions for a wide range of consumer electronics and personal computing devices. The 20 MHz operation modes will continue to be available to support applications where higher frequency reuse is desired due to the limited number of available non-overlapping channels.

802.11n should require support for at least two MIMO spatial data streams using SDM. Specifying support for at least two spatial data streams provides for architecture designs that can efficiently interoperate in high-throughput networks. Supporting at least two spatial data streams will require a minimum of two antenna AFEs on all 802.11n implementations. Support for more than two antennas or two spatial streams should be optional with the maximum number limited to four, for practical reasons.

Advanced features that may maximize throughput for those applications requiring the highest performance, may be implemented optionally. Advanced features of this type should be specified by 802.11n to ensure interoperability but allowed as optional for implementation only where they make sense. This would include features such as greater than two transmit antennas, channel adaptive beam-forming, and advanced FEC coding approaches (features not addressed in this article).

Managing PHY Performance Modes

When maximizing data throughput, intelligent mechanisms will be required to manage the selection of PHY layer performance modes. Although the MAC layer does not contribute directly toward increasing the physical transfer rate, it will play a key role in effectively optimizing selection of the PHY layer performance modes.

Fast channel adaptation should be managed at the PHY layer without MAC interaction. Once the initial adaptation is established, using OTA signaling in a timely fashion, the MAC layer will need to establish and maintain adaptation to wireless channel conditions. This will include managing the selection of MCSs, code rates, antenna configurations, channel bandwidths, and channel selection where optimization of TX/RX relationships can maximize throughput.

Improving Transfer Efficiency

A large contribution to overall throughput at the MAC SAP will result from new MAC features maximizing throughput efficiency. It is important to understand that as PHY layer rate is increased, the relative impact of PHY overhead also increases. At the same time, PHY headers and fixed overhead must increase to support the new advanced PHY layer modes described earlier.

One important approach to improving transfer efficiency is provided with new aggregate exchange sequences. An aggregate exchange is where multiple MPDUs are aggregated into a single PPDU. Aggregate exchange sequences are made possible with a protocol that acknowledges multiple MPDUs with a BAR. A BAR is requested with each aggregate exchange. This protocol effectively eliminates the need to initiate a new transfer for every MPDU. Using the existing MAC

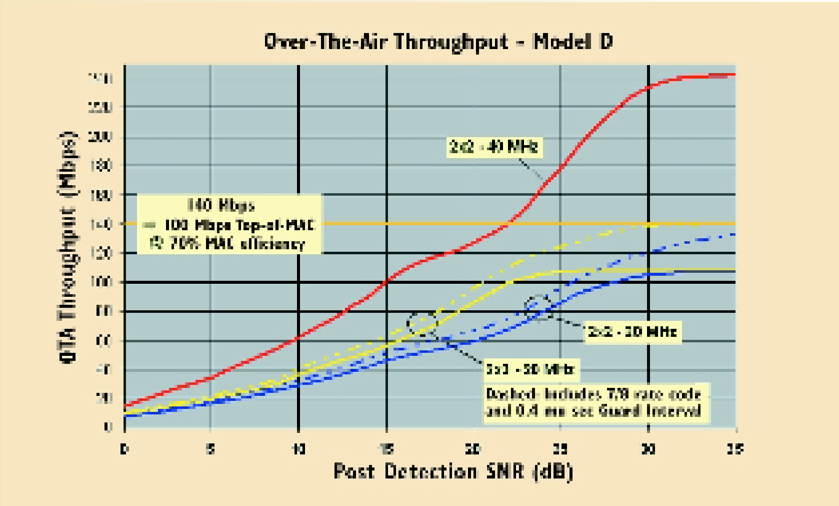

Figure 3. OTA throughput with different bandwidth channels.

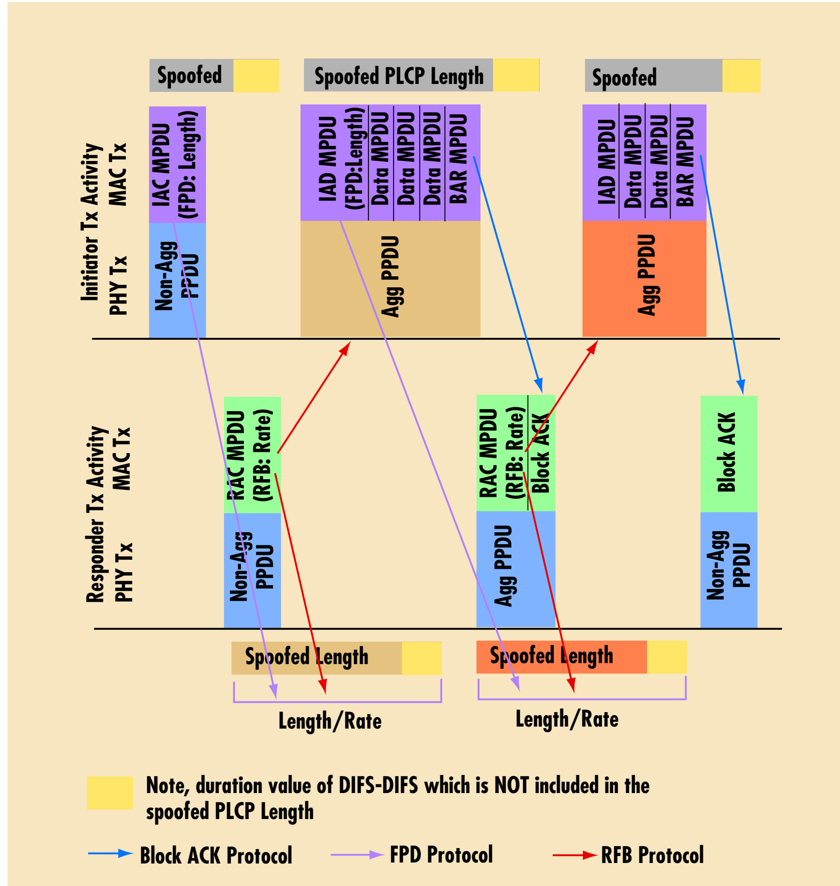

Figure 4. Bi-directional aggregated exchange sequence showing contention protection.

protocols without aggregation, a PHY rate of 500 Mb/s would be required to achieve a throughput of 100 Mb/s at the MAC SAP. Additional opportunities exist with new MAC mechanisms to transfer data in both directions also without initiating a new transfer. This approach allows a responder to aggregate MPDUs in a reverse direction in response to an *initiating station transfer*. Mechanisms are also possible that minimize turn around times between the initiator and the responder while ensuring contention protection within the BSS.

To more effectively transfer data and reduce connection overhead, aggregate PPDUs containing multiple MPDUs from a single source to a single destination are needed. Maximizing efficiency for this kind of capability will require PPDUs longer in length than the current standard allows (4095 bytes). A reasonable target for PPDU length is 64 Kb or greater. Aggregate PPDUs will also be able to transfer data to multiple destinations using new MPDU formats. This would be valuable for applications like VoIP where many stations need access, high BSS capacity with relatively low throughput per station requirements.

802.11 Legacy Coexistence

The IEEE TGn expects 802.11n backward compatibility with 802.11a/b/g devices. Legacy 802.11b devices will need to coexist, and legacy 802.11a/g devices should be expected to interoperate with 802.11n devices when operating in the same band and channel.

PPDU packets should be decodable without prior knowledge of transmission method. This is to say, legacy devices must be able to decode and disposition new high throughput packets, even if these packets are not intelligible to legacy devices. At the same time, seamless legacy (802.11a/g) interoperability (legacy devices operating in an 802.11n high throughput network) must be supported while minimizing performance penalties to high-throughput operation.

The MAC will be responsible for managing backward compatibility with existing legacy 802.11a/b/g devices. This will include coexistence for all legacy devices (802.11a/b/g) entering an 802.11n BSS. The MAC will also provide interoperability with supported modulation schemes (i.e., OFDM) in matching spectral environments (i.e., 2.4 GHz or 5.0 GHz bands as implemented). Coexistence mechanisms will need to manage channel bandwidth mismatches in mixed BSS environments and ensure mixed-mode operation is supported with low overhead interoperability between 802.11n and legacy 802.11a or 802.11g.

Summary

Presently, 802.11a/b/g WLANs provide adequate performance for today's networking applications where the convenience of a wireless connection can provide the user value. As next generation wireless applications emerge, higher WLAN data throughput will be required. In response to this need, both IEEE TGn and the Wi-Fi Alliance have set expectations for the next generation of WLAN performance.

The IEEE TGn minimum expectation for 802.11n is 100 Mb/s at the MAC SAP. 802.11n is expected to support all major platforms, including consumer electronics, personal computing, and handheld platforms, throughout all major enterprise, home,s and public hot spot environments. The broad scope of this vision advocates practical implementations that will operate robustly using technical approaches that may be developed and implemented cost effectively within the time frames targeted by IEEE TGn.

Key considerations in architecting the next generation of WLAN are cost and robust performance. Both MIMO technology and wider bandwidth channels will be required to reliably satisfy the higher throughput demands of next generation applications. At the same time, overall throughput at the MAC SAP will be enabled with new MAC features maximizing throughput efficiency.

More information on the development and industry status of 802.11n can be found on:

IEEE 802 Wireless World web site:
http://www.802wirelessworld.com/index.jsp

Wi-Fi Alliance website:
http://www.wifi.org/OpenSection/index.asp

TGn Sync website:
http://www.tgnsync.com/

WD&D

About The Author

James M. Wilson is a technical marketing engineer in the Communications Technology Lab, part of the Intel Corporate Technology Group. In 22 years at Intel, he has worked on mixed signal component development and test engineering, PC and server platform development and product introductions, and several wireless technologies including Bluetooth, home RF, 802.11, and ultra-wideband. He is working on radio interconnect technologies for future applications. James has a B.S.E.E.T. from DeVry Institute of Technology.