Today, the installed base of 802.11 (Wi-Fi) client devices exceeds 100 million worldwide. Wi-Fi radios are appearing not just in laptops and PDAs, but in equipment as diverse as mobile phones, parking meters, security cameras and home entertainment equipment, to name a few. With a large, diverse and rapidly growing installed base, the research and development investment in Wi-Fi remains very high. As a result, during the next few years Wi-Fi will continue to become faster, more secure, more reliable and more fully-featured. These advances will in turn drive continued adoption, which will then drive even more R&D investment. For this reason, the future of Wi-Fi as a client technology, indoors and out, is very bright indeed.
This technology brief reviews the progress made to date on standards under the IEEE 802.11 (Wi-Fi) umbrella. We also offer a preview of coming enhancements that will expand the applicability of 802.11 wireless technologies to new application areas. The results of the active work underway will be future industry-standard versions of Wi-Fi that run at 150+ Mbps data rate, have QoS support for applications such as voice and video, enable mobility-speed roaming for voice and much, much more.

Approved and near-term 802.11 Letter Standards

A number of amendments to the base 802.11 standard have been approved by the IEEE and implemented by manufacturers since 1997. These can be broadly categorized as follows:

- **Faster:** Physical Layer enhancements that employ higher order modulation schemes to increase the data rates deliverable over 802.11. Standards-based Wi-Fi now delivers data rates up to 54 Mbps to Wi-Fi clients.

- **Better-performing:** Quality of Service enhancements have modified the MAC (Media Access Control-the signaling scheme between transmitters and receivers) to provide admission control (regulating the amount of data contending for the wireless medium) and prioritized channel access. The need for a better-performing MAC has been driven by demanding applications such as voice and video. Better QoS enables and improves performance of these applications in addition to ordinary data traffic.

- **More secure:** Security enhancements have been developed to address access control and authentication (limiting access to the network to authorized users) and data privacy and integrity, driven by the market requirement for enterprise-level security in wireless LANs.

- **Broader applicability:** Regulatory enhancements that broaden the applicability of 802.11 to other frequencies such as 4.9 GHz in Japan and additional regulatory domains. These open up new markets to Wi-Fi technology including large parts of Europe and Asia. These enhancements have accelerated the volume of Wi-Fi shipments by making it the first truly global data radio standard.
A bit more detail on the evolution of 802.11 follows, including discussion of expected near-term enhancements.

**Physical Layer enhancements**

802.11a and 802.11b were approved in 1999. 802.11a, which defines a physical layer for operation in the 5 GHz unlicensed bands, uses OFDM modulation and provides raw data rates up to 54 Mbps. 802.11b, defines CCK modulation to deliver raw data rates up to 11 Mbps in the 2.4 GHz band. 802.11g, a backwards-compatible extension to the 802.11b standard in the 2.4 GHz band, was approved in 2003. It allows data rates up to 54 Mbps through use of OFDM or CCK modulations.

While 802.11g and 802.11a nominally offer higher data rates, it is important to recognize that these higher data rates will require much higher cell densities to realize in practice. For example, typical access points can provide 54 Mbps data rates only up to tens of feet whereas they can extend 11 Mbps data rates up to hundreds of feet. This is because the higher data rates require higher levels of signal-to-noise-ratio (SNR) at the receiver.

**Security enhancements**

802.11i, approved in 2004, defines strong authentication and access control mechanisms leveraging RADIUS (the most common form of subscriber directory) and 802.1x, an IEEE standard for securing LANs. The standard also defines 802.11 key management using 802.1x and support for stronger encryption and data confidentiality using TKIP and AES as well as stronger message integrity checking. 802.11i will make 802.11 wireless networks more secure and is expected to lead to broader adoption in enterprise settings.

WPA (Wi-Fi Protected Access) was adopted by the Wi-Fi Alliance in 2003. While not an IEEE standard, it is an interim proposal based on an early draft version of the 802.11i standard that was adopted because of the urgency of security needs. Designed to be a software-only upgrade to equipment already deployed, WPA includes TKIP and 802.1x authentication and dynamic key management.
Regulatory enhancements

802.11d (approved in 2001) and 802.11h (approved in 2003) extend the physical and MAC layer to allow 802.11 to operate in regulatory domains of other countries. Since regulatory requirements regarding the use of the 5 GHz band vary from country to country, the ITU (International Telecommunications Union) recommended a harmonized set of rules to allow unlicensed transmitters in this band to coexist with primary-use devices such as military radar systems in Europe. 802.11h defines mechanisms such as Transmit Power Control (TPC) and Dynamic Frequency Selection (DFS) to allow for licensed-unlicensed coexistence in the 5 GHz band. These rules allow unlicensed transmitters to employ more sophisticated versions of “listen-before-talk” to adjust the transmit power and intelligently select the operating channel so as to more efficiently use the available spectrum and to avoid causing harmful interference.

802.11j

Approved in 2004, 802.11j defined regulatory and protocol extensions to allow for operation in the 4.9GHz and 5GHz bands in Japan.

Future 802.11 Standards

The following standards, with the exception of 802.11s, are expected to be codified in 2005 or 2006. 802.11s will most likely be approved in late 2006 or 2007.

802.11k

802.11k is focused on standardizing the radio measurements that will allow uniform measurement of radio information across different manufacturer platforms. By having standardized, repeatable measurements, system designers can utilize radio environment information to make better decisions as to frequency use, transmit power levels, etc. This will lead to 802.11 networks that are easier to monitor and manage and that can make more efficient use of the available spectrum.

802.11n

The 802.11n Task Group is focusing on creating a standard to further increase the net throughput of wireless networks. The goal is to achieve greater than 150 Mbps data rate over an 802.11 communications channel. Both physical and MAC layer changes are being considered, but backward compatibility is required. This new standard will enable 802.11 to meet the growing need for more data-intensive applications as well as aggregating traffic from multiple access points or cells together.
802.11r
The 802.11r Task Group is working on reducing the handoff latency when client devices transition between access points or cells in an Extended Service Set comprising access points in the same network. Faster handoffs will be critical to meeting the real-time requirements of delay-sensitive applications such as voice, especially in mobile settings where client devices can be expected to roam frequently. This standard will facilitate the deployment of SIP-based Voice over Wi-Fi (VoWi-Fi) portable phones.

802.11s
The 802.11s Task Group is working on an infrastructure mesh standard to allow 802.11 access points or cells from multiple manufacturers to self-configure into multi-hop wireless topologies. We expect that a mesh standard would enlarge the range of markets and applications for the 802.11 standard. Example usage scenarios for mesh networks include interconnectivity for devices in the digital home, unwired campuses, and community area networks or hotzones. The standard is expected to be designed to be extensible by manufacturers to enable diverse usage scenarios with differing functional requirements. For example, some applications may require quick ad-hoc setup and teardown of a mesh while others require large scale and maximum throughput.

Standards Evolution of 802.11

Over the last several years the successive enhancements to the MAC and Physical Layer have dramatically increased the system capacity of 802.11 networks. Early work, focused on higher order modulation schemes, has delivered peak raw data rates up to 54 Mbps over a 20 MHz channel. The currently active 802.11n Task Group is looking into ways to further increase maximum data rates to more than 150 Mbps using a variety of approaches including channel bonding and MIMO (Multiple Input, Multiple Output) technology.

The chart to the right illustrates the evolution of the standard’s ability to support higher data rates.
More generally, the last several years have seen considerable progress on 802.11 technologies on a variety of fronts, in addition to the continually increasing data rates:

- Radio and regulatory extensions have increased the scope and applicability of the standard across different regulatory domains with differing incumbent operators, different unlicensed frequency bands and different spectrum rules.
- Early 802.11b deployments uncovered some serious shortcomings in the area of security – these have now been addressed through the 802.11i amendment that greatly increases security in the areas of authentication, access control and data privacy and integrity.
- QoS extensions defined in the 802.11e draft will provide fuller support for demanding applications such as voice or video in addition to providing prioritized access on a per-user or per-application basis. Coming enhancements such as 802.11r will support faster handoffs, improving application performance for mobile devices.
- The 802.11s Task Group is in the process of defining a mesh architecture overlaid on 802.11 that would allow for adaptive, self-configuring and fault-tolerant mesh networks that would expand the applicability and utility of 802.11 networks into hard-to-wire areas and larger campuses.

### Extensions to the Base (802.11) Standard

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Amendments in RED indicate standards that are not yet approved.
Conclusions

Wi-Fi has experienced tremendous adoption in the last several years. The adoption and success of Wi-Fi have fueled considerable activity and investment in 802.11 standards development that have resulted in significant extensions in the capabilities of the standard. As a result, Wi-Fi is getting faster, more full-featured and more secure even as manufacturing volumes continue to reduce per-unit costs. The enhancements to the Wi-Fi standards are addressing and enabling new markets, new applications and new usage scenarios. These developments will continue to drive adoption and further investment leading to the further growth and maturity of the standard.