Wireless local area networks (LANs) based on the IEEE 802.11 standard [1] have been deployed extensively in recent years for both indoor and outdoor applications. The proliferation of 802.11 wireless fidelity (Wi-Fi) enabled devices such as laptops, personal digital assistants (PDAs), smart phones, cell phones, and access points is reflected by semiconductor shipments data. During 2006, almost 200 million Wi-Fi chip sets were shipped, accumulating to a total of 500 million. A total of one billion are forecasted to be shipped by mid-2008 [2], and global semiconductor revenues are expected to reach US$4.1 billion by 2011 [3]. The main reasons for the unprecedented success of Wi-Fi-based networks include the following:

- **Unlicensed Spectrum**—Operation in the 2.4-GHz ISM (industrial, scientific, and medical) band and the 5-GHz U-NII (unlicensed national information infrastructure) bands substantially reduces the capital expenditure (CAPEX) and the operational expenditure (OPEX) of indoor/outdoor Wi-Fi networks. Reduction of the overall costs enables free or low-cost high-data-rate services. For comparison, 3G operators have spent billions of dollars for spectrum licensing which enabled data services comparable to Wi-Fi’s cost-effective data services for stationary and nomadic users.

- **High Throughputs**—Physical layer (PHY) rates up to 54 Mb/s are supported for single-input, single-output (SISO) modes (20-MHz channel with one spatial stream) and PHY rates up to 600 Mb/s will be supported with multiple-input, multiple-output (MIMO) (40-MHz channel with four spatial streams). Achievable per-user SISO mode throughputs in a multi-user scenario are in the range of several hundred kb/s to several Mb/s depending on channel conditions, number of users, and medium access control (MAC) utilization, as explained in the last section. Achievable per-user MIMO mode throughputs are expected to be substantially higher [4].

- **Robustness**—The MAC layer is based on the carrier sense multiple access/collision avoidance (CSMA/CA) protocol [5], which enables a Wi-Fi device to co-exist with Wi-Fi and non-Wi-Fi interferers such as cordless phones, Bluetooth devices, and microwave ovens. In addition, the PHY layer employs adaptive modulation techniques, which automatically adjusts packet data rate according to dynamic channel and interference conditions.

- **Very-Low-Cost Silicon**—The cost of a complete Wi-Fi chip set that includes the PHY, MAC, and radio frequency (RF) modules is less than US$10. Low-cost Wi-Fi chip sets enable the production of very low bill of material (BOM) consumer- and carrier-grade equipment. The BOM of consumer level client network interface cards (NICs) and access points is on the order of few dozens of dollars.

- **Backward Compatibility**—A key feature of all IEEE 802.11 set of standards are extensions enabling the most recent Wi-Fi chip set to fully communicate with the oldest version of chip sets, which are over ten years old.
The IEEE 802.11 standard was initially published during 1997, specifying a wireless LAN protocol for the 2.4-GHz ISM band. The standard defined a MAC layer based on the CSMA/CA protocol and a PHY layer supporting data rates of 1 Mb/s and 2 Mb/s based on direct sequence spread spectrum (DSSS) modulation, occupying 20-MHz channels. In 1999, the IEEE 802.11b [6] supplement for high-data-rate extension in the 2.4-GHz band was published, adding to the 802.11 two new data rates of 5.5 Mb/s and 11 Mb/s based on complimentary code keying (CCK) modulation [5]. Additionally, during the same year, the 802.11a [7] supplement was published, specifying a high-speed PHY layer in the 5-GHz band. This new PHY layer did not support the 802.11b rates (1, 2, 5.5, and 11 Mb/s) and was based solely on orthogonal frequency division multiplexing (OFDM) modulation. The following data rates were defined: 6 and 9 Mb/s with binary phase shift keying (BPSK) modulation, 12 and 18 Mb/s with quadrature phase shift keying (QPSK) modulation, 24 and 36 Mb/s with 16-quadrature amplitude modulation (16-QAM), and 48 and 54 Mb/s (64-QAM). In 2003, the 802.11g [8] amendment for further high-data-rate extension in the 2.4-GHz band was published. This amendment added the 802.11a set of data rates to the 802.11b set of data rates, thus defining the full range of rates from 1 Mb/s up to 54 Mb/s for the 2.4-GHz band. The 802.11n (draft 2.0) is the most recent PHY and MAC amendment for enhancements for higher throughput in the 2.4- and 5-GHz bands. The 802.11n defines a MAC layer with improved efficiency and a new PHY layer based on MIMO communications supporting up to four spatial streams and channel bandwidths of either 20 or 40 MHz. The maximum specified data rate is 600 Mb/s.

The migration from small-scale indoor networks to large-scale outdoor networks is driving additional amendments to the standard:

- 802.11s—Mesh Networking
- 802.11e—QoS (Quality of Service) Enhancements for Voice and Video
- 802.11i—MAC Security Enhancements
- 802.11h—Transmit Power and Spectrum Management
- 802.11k—Radio Resource Management
- 802.11r—Fast Roaming Between Access Points (mainly for Voice over IP).

Outdoor Wi-Fi networks have penetrated markets such as municipal Wi-Fi, wireless digital subscriber line (DSL) services, and private networking for homeland security first responders (extension of the 802.11a to the 4.9-GHz licensed spectrum). In these markets, Wi-Fi operators are competing with carrier-grade broadband access services such as xDSL, cable, wireless local loop (WLL), and high-speed 3G data services. A carrier-grade outdoor Wi-Fi network is expected to meet the following requirements: deliver extremely reliable service with low mean time between failures (MTBF), provide secure access links to all customers, enable network control and monitoring by a network management system (NMS), and fully support the operator’s authentication and billing infrastructure.

Outdoor Wi-Fi networks are cost-effective infrastructure for wireless Internet service providers (WISPs) either for green field deployments or for competition with existing services. For example, a WISP can provide Internet service for hotel guests by installing outdoor access base stations (BSs) only in the streets surrounding the hotel and exploiting the in-building penetration capabilities of the Wi-Fi signals to compete with the internal wired or wireless broadband service. In areas where the infrastructure is limited, the government or municipality can encourage advanced data services by providing Wi-Fi-d broadband access [9]. When disaster strikes, emergency first responders' ability to command, coordinate, and control their actions is greatly improved and risks are mitigated with wireless broadband communications capabilities. Recent U.S.-based natural disasters have prompted federal, state, and local (municipal) agencies to explore public safety solutions. Hurricane Katrina’s impact on the Gulf Coast provided a case study on how poorly the government first responders were prepared to coordinate large-scale rescue and relief efforts. Planned in advance, wireless networking technology like outdoor Wi-Fi can improve public safety response to disasters. While a disaster of a smaller scale, the 1 August 2007 Minneapolis I35W bridge collapse provided an example of municipal Wi-Fi's value to first responders [10]. A nearby Minneapolis Municipal Wi-Fi network was rapidly extended with wireless mesh coverage to the bridge area by its WISP, USI Wireless. First responders were able to use wireless broadband Internet connectivity where there had been none just a few hours before the disaster struck.

Figure 1. Distribution of measured delay spreads in suburban environment.
In this article, we provide insight into outdoor Wi-Fi deployment challenges as well as into NextWave Wireless’ carrier-grade Wi-Fi solution, with emphasis on mesh network architecture and adaptive antenna technology, which are key components in enabling a competitive service.

Outdoor Wireless LAN Deployment Challenges

The IEEE 802.11 standard was originally designed for indoor applications in which a small number of clients are attached to a single access point with no need for network infrastructure scalability. Furthermore, this design considered a small number of local interferers, as outdoor low-power interferers are attenuated by in-building penetration loss and mostly received below noise level of the indoor access point. Deploying outdoor Wi-Fi networks poses several significant challenges, which may degrade network performance and economical competitiveness if not remedied:

1) Long Multipath Delay Spreads—All IEEE 802.11 PHY specifications were designed for limited delay spread values which are typical of indoor environments: <0.8us for 802.11g and <0.4us for the 802.11n using short guard interval mode. Given these maximum delay spread values, Wi-Fi receivers incorporate limited equalization techniques that cannot handle higher delay spread values. Figure 1 displays the delay spread distribution of approximately 1,000 wireless channel impulse responses, captured in the city of Henderson, Nevada (typical suburban environment). It is evident that values on the order of 3 us and beyond are common, which implies that PHY performance will be degraded even in medium/high signal-to-noise ratio (SNR) scenarios due to intersymbol interference (ISI) which cannot be compensated by the equalizers of the Wi-Fi receivers.

2) Network Scalability—Wireless networks are typically deployed in several phases: the initial deployment is primarily focused on coverage, and later phases are focused on increasing capacity by filling in cells. Providing an economical network-scalable solution is fundamental for Wi-Fi networks to compete with other carrier-grade networks.

3) Unbalanced and Limited Link Budget Conditions—Major regulatory bodies have defined effective isotropic radiated power (EIRP) limitations for the unlicensed bands. This limitation gives rise to imbalanced uplink (UL) versus downlink (DL) link budgets, which limit range and indoor penetration. Table 1 presents 2.4-GHz regulations as defined by the U.S. Federal Communications Commission (FCC) [11] and the European Telecommunications Standards Institute (ETSI) [12]. Adaptive antenna techniques that utilize array and diversity gains are a natural choice for substantial performance improvements, given the regulatory constraints.

4) Interference Mitigation—The constantly increasing usage of outdoor unlicensed spectrum substantially exacerbates interference environment conditions of outdoor Wi-Fi BSs compared to indoor conditions. In addition, outdoor Wi-Fi BSs may be equipped with high-gain antenna and mounted on a roof top or a mast. This type of deployment gives rise to substantially larger coverage radius with more sources of interference compared to low-altitude, low-antenna-gain Wi-Fi BS deployments. High levels of interference translate into significant transmission delays due to the contention-based MAC mechanism, which further degrades throughput and QoS performance.

Network and Mesh Architecture

NextWave Wireless’ carrier-grade Wi-Fi network [13] architecture is depicted in Figure 2. The network is fully scalable and supports coverage of large areas by splitting the overall network into clusters. Each cluster is composed of one to two dozen Wi-Fi BSs. All BS models have been designed to operate in extreme outdoor temperature conditions to meet MTBF >50,000 h. The access protocol between the BSs and the clients is 802.11b/g enhanced by adaptive antenna technology, operating in the 2.4-GHz ISM band. All clusters are connected via a 5-GHz wireless backhaul to the operator’s local network. The local network is connected to a data center [AAA authentication server, Voice over IP gateway (GW)] and network operations center (NOC) from which the entire network is managed by the NMS. Every client that is connected to the network and has successfully authenticated itself via the AAA server can access the Internet via an access controller.

A key enabling technology of economical large-scale Wi-Fi cluster deployments is mesh networking [14]. The mesh is a dedicated Wi-Fi-based backhaul network which intraconnects all Wi-Fi BSs within a single cluster. The mesh radios operate in the 5-GHz U-NII bands (employing the 802.11a standard), thus not interfering with the access radios operating in the 2.4-GHz ISM band. Key advantages of Wi-Fi mesh technology include:
• Reduced CAPEX: There is no need for wired backhaul per Wi-Fi BS, only a power cable.
• Reduced OPEX: This is due to the use of U-NII bands for backhauling.
• Scalability: The serviced area can be easily expanded by adding new nodes that autonomously join the mesh network.
• Rapid Installation: By employing wide-beamwidth antennas, each node configures itself within the mesh without the need for fine antenna orientation adjustments.
• Self-Healing Topology: Dynamic routing protocols enable real-time detection of inferior quality mesh links and transition to superior quality one.

NextWave Wireless’ mesh architecture is implemented according to the 802.11s evolving amendment for 802.11-based mesh networks. The 802.11s amendment defines a layer 2 wireless distribution system (WDS) that enables automatic topology learning and routing. In every Wi-Fi cluster, a single BS is defined as the mesh GW, and all other BSs are defined as mesh nodes. The Mesh GW is connected to the operator’s backbone, and all traffic in and out of the cluster passes through it. Each mesh GW or node is equipped with a dual radio for the mesh traffic which enables flexible and robust frequency planning. The dual radio technique is superior to a single radio mesh which forces a single frequency channel to be used across the entire cluster. Dual radio mesh networks benefit also from substantially reduced per-hop delay (compared to single radio), which is critical for delay-sensitive traffic such as Voice over IP. This advantage is due to the reduced contention periods while bridging packets between the two RF frequencies, compared to a single RF frequency network in which all nodes are contending simultaneously for the same medium. A common topology for the mesh is a tree, as depicted in Figure 3. For this case, the mesh GW is defined as the “root” of the tree and all nodes that connect to it are defined as its “sons.” Every son has a single father and either zero, one, or several sons. The tree structure is determined by a distributed mechanism—whenever a new mesh node is installed and powered up, it initiates a “father
selection” process in which all candidates are scanned and the father that has the best RF link towards the scanning node is selected. Routing within the mesh is performed using two mechanisms:

- **Routing Tables**—The GW and all nodes hold a table with one entry for the father BS ID and an additional entry per each associated client with the ID of the son BS via which the client is associated, as depicted in Figure 4.

- **WDS Addressing**—This technique uses all four available addressed in the IEEE802.11 MAC header [5] as follows: 1) next hop BS MAC address, 2) originating BS MAC address, 3) destination station MAC address, and 4) source station MAC address. Figure 5 describes an example of this address mode.

The capacity of the mesh tree is a function of several parameters, as follows:

- **GW Capacity**—The aggregated tree capacity is limited by the capacity of the backhaul link between the GW and the operator network.

- **Number of Nodes**—The GW capacity is shared between all mesh nodes. Increasing the number of nodes causes a decrease in total capacity [15], and the capacity of each node decreases as $O(1/n)$, where $n$ is the total number of nodes [16].

- **Tree Structure**—A large number of hops between nodes and the GW introduces delays that progressively degrade capacity. Advanced generations of mesh networks mitigate this effect by using multiple radios: access and mesh radios operate at different RF bands and the mesh employs multiple channels per node, thus reducing per-hop delays. The capacity of dual-channel mesh is shown in [17] to outperform single-channel mesh by factors of 6 to 7.

- **Antenna Type**—Mesh links that employ directional antennas enjoy higher rates due to better link budgets and reduced interferences compared to omnidirectional antenna-based mesh links.

### Adaptive Antenna Technology

NextWave Wireless’ carrier-grade Wi-Fi BSs are enhanced by adaptive antenna technology. Adaptive antenna (also known as adaptive beamforming) technology [18] has been applied to various military and commercial wireless systems such as phased array radar and cellular networks [19]. An adaptive antenna system consists of an array of $M$ antenna elements (either omnidirectional or directional). Transmit and receive baseband signals from all elements are processed by a digital signal processor (DSP) prior to transmission (and up conversion) or post reception (and down conversion), respectively. The DSP forms dynamically UL and DL beam patterns, thus enhancing system performance. The most common array topologies are uniform circular array (UCA) and uniform linear array (ULA).

In the following, we explain key advantages of adaptive antennas as applied to outdoor Wi-Fi systems:

- **Array Gain**: An antenna array with $M$ elements enjoys an additional gain on top of the single-antenna element gain which is equal to

  \[ \text{Array Gain} = 10 \log_{10} M. \]

  For instance, the array gain of a four-element array is 6 dB (for UL and DL). Therefore, the total gain of the array is 6 dB + single-element gain [dB]. Array gain is an efficient technique to improve UL link budget for FCC and ETSI environments. In addition, it also enables DL link budget improvement via EIRP increase according to FCC regulations.

- **Diversity Gain**: Signals that propagate through wireless channels are subject to fading conditions which degrade signal quality at the receiver. Spatial diversity techniques [20] are well known to efficiently combat fading without sacrificing power or bandwidth. These techniques can be applied either at the receiver or transmitter. During reception, independent copies of the received signal (from each antenna element) are combined optimally or suboptimally, thus reducing the probability that the combined signal is faded. The
diversity gain reflects the improvement in the link budget. Figure 6 presents prediction analysis of the diversity gains of a four-element ULA in a typical suburban environment, based on real-life spatial channel impulse responses measured in the city of Henderson, Nevada. The results indicate that this scheme (based on optimum diversity combining [21]) extracts diversity gains of at least 4 dB in 50% of the channels measured in this location. Utilizing channel reciprocity in TDD systems [20] enables one to employ transmit diversity schemes that can improve DL link budget limitations for the ETSI environment.

• **Interference Reduction**: Adaptive antenna systems can utilize the fact that an interfering signal may arrive from a different direction than that of the desired signal. The array can be configured to direct a null to an interfering transmitter direction or it can be configured to apply a spatial filter which has significant side-lobe attenuation. For example, a four-element array provides at least 12-dB attenuation of signals arriving from side lobes, as depicted in Figure 7.

Combining adaptive antenna technology in outdoor Wi-Fi systems provides link budget improvements that can be leveraged to range extension, improved in-building penetration, interference mitigation, and capacity enhancement.

In the following, we demonstrate how adaptive antennas are utilized to extend range and increase capacity by comparing a single-antenna Wi-Fi BS and an adaptive-antenna-based Wi-Fi BS. These enhancements are further shown to improve overall network CAPEX and OPEX. We assume in our analysis a Wi-Fi BS that employs a four-element ULA. The gain of each element is assumed to be equal to 12 dBi. The adaptive antenna scheme applied by the system is digital beam-steering. This scheme extracts full array gain for both UL and DL. The utilization of the beam-steering technique is performed as follows: In reception mode, the adaptive antenna estimates the direction of arrival (DOA) of the incoming Wi-Fi packet. Based on the estimated DOA, a beam...
is formed digitally in the direction of the estimated DOA and kept constant during the entire packet period (up to several ms). In transmission mode, the system transmits the Wi-Fi packet by forming a beam towards the estimated DOA of the specific client, which is also kept constant during the entire packet duration. Since Wi-Fi is a multi-user system, the estimated DOA of each user is stored in a dedicated look-up table. An additional significant advantage of the beam-steering mechanism is multipath reduction. Multipath channel taps whose angle of arrival is different from the pointing direction of the adaptive beam are attenuated by at least 12 dB, thus substantially reducing ISI.

### Performance Evaluation

The performance evaluation is based on calculating the maximum DL and UL range of every PHY rate supported by the 802.11g standard. The maximum cell radius of each system is defined by the minimum between the UL and DL ranges. The performance is analyzed using the log-distance path loss model [19], which is based on a dual slope propagation assumption:

- **First slope**: Line-of-sight (LOS) propagation (path loss exponent $n = 2$) along a clearance distance of $d_0$ m from the transmitter.
- **Second slope**: Non-LOS propagation ($n > 2$) along the path from $d_0$ m until the receiver.

### Figure 8

*PHY rates and range of four-element ULA system versus single-element system: (a) DL and (b) UL.*

### Table 2

<table>
<thead>
<tr>
<th>BS Type</th>
<th>Single-Element</th>
<th>Four-Element ULA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element Gain</td>
<td>12 dBi</td>
<td>12 dBi</td>
</tr>
<tr>
<td>BS EIRP</td>
<td>36 dBm</td>
<td>44 dBm</td>
</tr>
<tr>
<td>Client EIRP</td>
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<td>15 dBm</td>
</tr>
<tr>
<td>Thermal Noise Power</td>
<td>−95 dBm</td>
<td>−95 dBm</td>
</tr>
<tr>
<td>Array Gain</td>
<td>0 dB</td>
<td>6 dB</td>
</tr>
</tbody>
</table>
The following parameters were used in our analysis:

- clearance distance \( d_0 = 10 \text{ m} \)
- non-LOS path loss exponent \( n = 4 \), which is typical for urban environments
- center frequency of 2.437 GHz.

For the BS parameters, we assume that both systems utilize 12-dBi antenna elements. According to an FCC ruling, for the single-antenna system the EIRP is limited to 36 dBm. For the multibeam antenna array system, the EIRP is calculated as follows (see Table 1):

\[
\text{EIRP} = 36 \text{ [dBm]} + \frac{2}{3} \times (12 \text{[dBi]} + 6 \text{[dB]} - 6 \text{[dB]}) = 44 \text{ dBm}.
\]

The client output power is assumed at 15 dBm and client antenna gain is assumed at 0 dBi. Table 2 summarizes the BS and client parameters.

According to the IEEE 802.11g standard [8], the sensitivity of each rate is defined as the minimum input power level required to receive a 1,000-B packet with less than 10% packet error rate (PER). The 10% threshold is considered by the IEEE 802.11 standard as an upper limit for reliable communications at a given PHY rate. The sensitivity level of each PHY rate is calculated as follows:

\[
\text{sensitivity (PHY rate) [dBm]} = \text{thermal noise power [dBm]} + \text{SNR (10\% PER of the PHY rate) [dB]},
\]

Table 3 summarizes the sensitivity levels of all rates as defined in [1], [6], and [7], assuming −95 dBm thermal noise power.

![Figure 8](image8.png)

Figure 8 presents DL and UL rates and ranges of the ULA BS versus the single-antenna BS. The DL range of the ULA system is 934 m and for the single-antenna system it is 589 m. The UL range is 496 m for the ULA system and 351 m for the single-antenna system. Given these results, we conclude that the range of the ULA system is 496 m and the range of the single-antenna system is 351 m, which amounts to 41% range extension. In terms of covered area, the 41% range extension gives rise to 100% area extension, according to the ratio of the squared cell’s radius. Hence, the density of the ULA system is theoretically 50% less than the density of the single-element system under FCC regulation.

The overall range and UL data rates of both systems are depicted in Figure 9. Single user capacity is a function of MAC efficiency and the total number of active users. For example, a single user with PHY rate of 54 Mb/s can achieve 25–30 Mb/s of MAC throughput (MAC efficiency \( \sim 50\% \)) [22]. Adding more users reduces MAC efficiency [15], and the per-user capacity is given by \( C(n)/n \), where \( n \) is the total number of users and \( C(n) \) is the total capacity for \( n \) users.

The range analysis above assumed uniform propagation conditions; however, the topography is often nonuniform and BS density is further dependent on the specific covered area as well as installation constraints. In the following, we provide average BS densities based on NextWave Wireless’ extensive deployment experience in the U.S. market: for dense urban areas up to 30 BSs per square mile, for suburban areas up to 24 BSs per square mile, and for rural areas up to 12 BSs per square mile. These densities are 30% to 40% lower than common numbers in the market [23] due to the range extension gained by employing adaptive beamforming technology. Specifically, the limited client power is claimed in [23] to limit cell radius. However, the adaptive beamforming system compensates this limitation by utilizing the array gain to increase UL link budget; thus UL range is improved in spite of the limited client output power.

The CAPEX of a wireless network is the sum of the wireless

<table>
<thead>
<tr>
<th>Rate [Mb/s]</th>
<th>1</th>
<th>2</th>
<th>5.5</th>
<th>6</th>
<th>9</th>
<th>11</th>
<th>12</th>
<th>18</th>
<th>24</th>
<th>36</th>
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<td>−75</td>
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<td>−87</td>
<td>−84</td>
<td>−81</td>
<td>−75</td>
<td>−73</td>
</tr>
</tbody>
</table>

**Table 3. Sensitivity levels of 802.11B/G PHY rates.**

![Figure 9](image9.png)

**Figure 9.** Cell range and UL data rates of four-element ULA system compared to single-element system.
infrastructure costs (i.e., BS and backhaul equipment) and site acquisition costs. Assuming that the single-antenna system and the ULA system are sold at the same price, the CAPEX of the adaptive antenna Wi-Fi network is realistically 30–40% lower than that of the single-antenna Wi-Fi network. Following this argument, the OPEX is also reduced by 30–40%, assuming proportional reduction in site rental costs and technical support expenses.

Conclusions
Implementing a carrier-grade Wi-Fi network is a challenging task. The network is expected to operate in extreme temperature and humidity conditions, provide highly reliable and secure data links to all customers, provide a centralized NMS, and interface to the operator’s authentication and billing infrastructure. NextWave Wireless’ Wi-Fi network has been designed to support all of the above carrier-grade features. In addition, mesh technology has been demonstrated to provide a cost-effective and survivable backhauling solution. Adaptive antenna technology has been demonstrated to improve the range and throughput of Wi-Fi BSs, thus reducing CAPEX and OPEX of the network and providing a competitive solution versus other carrier-grade Wi-Fi networks.

Acknowledgments
The authors are grateful to Ferdo Ivanek and Gadi Perets for their valuable suggestions and comments.

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[12] Radio Equipment and System (RES): Wideband transmission system; Technical characteristics and test conditions for data transmission equipment operating in the 2.4 GHz ISM band and using spread spectrum modulation techniques,” ETS1, ETS 328, 1996.


The sensitivity of each rate is defined as the minimum input power level required to receive a 1,000-B packet with less than 10% packet error rate (PER).