Developing integrated antenna subsystems for laptop computers

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The design, development, testing, and integration methodology for antennas integrated into laptop computers is described. Two key parameters are proposed and discussed for laptop antenna design and evaluation: standing wave ratio (SWR) and average antenna gain. A novel averaging technique was developed and applied to these to yield a measurable, repeatable, and generalized metric. A prototype antenna was built using this methodology, and measurements indicate that the resulting design attains both performance and cost targets. A PC-card-version wireless system is also discussed and compared with the integrated one. The impact of the antenna on the overall wireless system is studied through a link budget model.

Introduction

Wireless use by mobile professionals has increased greatly in the past several years [1–4]. According to Cahners–Instat, the market for wireless LANs is projected to grow from $1.2 billion in 2000 to more than $5.6 billion in 2005. Another estimate from Frost and Sullivan forecasts that manufacturers' revenue in the total worldwide wireless LAN industry will approach $884 million by the year 2005 [5]. As a result, the unlicensed 2.4-GHz industrial, scientific, and medical (ISM) band has become very popular and is now widely used for several wireless communication standards. Examples now include many laptop computers with built-in 11-Mb/s wireless LAN capability (standard 802.11b), and the newly developed Bluetooth technology for cable replacement to connect portable and/or fixed electronic devices. For even higher data rates, standard 802.11a devices in the 5-GHz Unlicensed National Information Infrastructure (U-NII) band are being developed which have data rates up to 54 Mb/s with proposed channel bonding techniques that will extend this to 108 Mb/s [6].

The initial implementations integrated these systems into portable platforms such as laptop computers using PC cards inserted into the PC card slot. As wireless technology becomes more prevalent and less expensive, manufacturers are moving away from PC cards in favor of integrated implementations. There is an industry-wide effort to avoid the problematic issues of breakage and physical design constraints associated with external antennas, and to completely integrate these communication subsystems directly into the portable platforms such as laptops. Until now, system designers did not take into account the wireless subsystem and the design did not include an antenna, when in reality integrated antennas can provide product differentiation [7]. There are a plethora of articles [8, 9] regarding all of these systems, but few designs fully integrate the antenna as part of the system and platform or achieve the potential performance such integration can offer. The goal of this paper is to highlight the specific design challenges associated with antenna integration into laptops. These challenges are illustrated through practical design examples, including suggested test and integration methodology to solve the problems outlined below.

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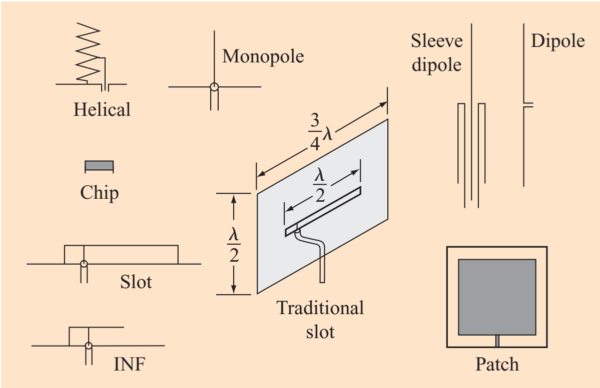

Figure 1

Antennas for laptop applications.

There are three major challenges for antenna design associated with wireless integration into laptops. First, laptops are very densely packed electronic devices, and there is little room for additional functions. Second, FCC emission requirements have forced laptop manufacturers to make extensive use of conducting materials in the covers of the laptops or conducting shields just inside the laptop covers to minimize radiation from today's very high-speed processors. Thus, it is difficult to place an antenna in an environment free enough of other conductors to create an efficient radiator. Third, the size, shape, and location of the antenna may be affected by other design constraints such as the mechanical and industrial design. It is therefore necessary to make engineering tradeoffs in the design, performance, and placement of the antenna on the one hand (given the industrial and mechanical design) and the size of the laptop on the other. As an example, early results based strictly on analytical modeling, blind cut-and-try, or the use of "integratable" vendor solutions yielded an integrated Bluetooth antenna solution incapable of reliable connectivity much beyond 1–3 meters; this was not even close to the advertised Bluetooth specification of 10 meters. Surprisingly, vendor solutions that touted fully integrated design capability for Bluetooth appeared to be measurements of freestanding antennas. Once integrated with the odd ground planes and cabling of a real system, the antennas fell far short of advertised performance. Selling an integrated system solution that falls short of user expectations creates disappointment and dissatisfaction, and could discourage wide acceptance of wireless technology. Clearly, a better solution to this problem was required.

Laptop-related antenna issues

Possible antennas for laptop applications

Figure 1 shows several possible antennas for laptop applications. Dipole and sleeve dipole antennas are basically the same, except that one is center-fed and the other is end-fed. Dipole antennas have a wider bandwidth than sleeve dipoles, but sleeve dipoles are easier to use. These antennas produce their best performance if they are mounted on the top of the display. Helical and monopole antennas should also be placed on the top of the display to achieve their best performance. The helical antenna is physically small, but its bandwidth is narrower than that of the monopole antenna, making it problematic to match transmitter and receiver over the fairly broad ISM bands. Given their large size, traditional slot and patch antennas should be placed on the surface of the display. Ceramic chip antennas are typically helical or inverted-F (INF) antennas or variations of these two types with high dielectric loading to reduce the antenna size. They are small, but their bandwidth is too narrow. Slot and INF antennas belong to the same antenna category and are good candidates for laptop applications because of their broader bandwidth characteristics. These antennas are also very popular for laptop applications because of their overall performance, ease of integration, simple design, and low cost.

For the traditional slot antenna, a slot, usually a half-wavelength long, is cut from a large (relative to the slot length) metal plate. The center conductor of the coaxial cable is connected to one side of the slot, and the outside conductor of the cable is connected to the other side of the slot. The slot antenna has very large impedance at the center of the slot and nearly zero impedance at the end of the slot. The feeding point is off-center to provide 50-Ω impedance and can be easily tuned by sliding it one way or the other.

The slot and INF antennas have similar impedance characteristics. That is, the feed point is moved to the slot end to decrease impedance (short end for the INF antenna) and the feed point is moved to the slot center (open end for the INF antenna) to increase the impedance. The slot length is a half-wavelength long for the slot antenna and a quarter-wavelength long for the INF antenna. Therefore, the length of the INF antenna is half the length of the slot antenna. This is an advantage, since, in many applications, the space allocated for an antenna is very limited.

The slot antenna can be considered as a loaded version of the INF antenna. The load is a quarter-wavelength stub. Since the quarter-wavelength stub itself is a narrow-band system, the slot antenna has bandwidth narrower than that of the INF antenna. This is another advantage of the INF antenna over the slot antenna.

The slot and INF antennas also have different radiation characteristics. For most implementations, the INF antenna has two polarizations, and the radiation pattern is relatively omnidirectional. This is the third advantage it has over the slot antenna. The slot antenna has primarily one polarization, and the radiation pattern is less omnidirectional than that of the INF antenna. However, the slot antenna tends to radiate more energy in the horizontal direction, and therefore has more useful energy for wireless LAN applications than does the INF antenna.

Mechanical and industrial design restrictions

For laptop applications, the laptop itself is an integral part of the overall antenna system. Most antenna systems used for laptops can be considered as "dipole-like" antennas. The antenna itself is one part (or monopole) of the dipole, and the other part is provided by the laptop. Antenna designers also view the laptop as the basic antenna element and the antenna itself as a tuning element. Since the laptop itself plays such a crucial role for the integrated antenna design, it is very important to study the antenna placement on laptops.

Figure 2 shows some typical antenna locations and types for laptops. Although the sleeve dipole and monopole antennas have very good performance, they are mechanically weak, expensive to make, and unattractive. Industrial design trends discourage putting anything visible on the surface of the laptop display in order to maintain a thin and sleek appearance. Consequently, the placement of patch and chip antennas on the surface of the display is avoided. Chip and INF antennas exhibit unacceptable performance if they are placed on the side of the laptop base. Base-mounted antennas suffer not only from effects due to the shadowing of the laptop system, but also from external environmental influences such as metal desks and the effects of a user's hands or lap. A metal desk may significantly shift the tuning of the antenna and create unwanted reflections that alter the omnidirectionality of the antenna. Absorption of the rf signal by a laptop user's hands and lap can have a dramatic effect on the effective antenna gain when the antenna is placed in the base of a laptop. Overall, an antenna should be placed on the top or close to the top of a display to achieve best coverage.

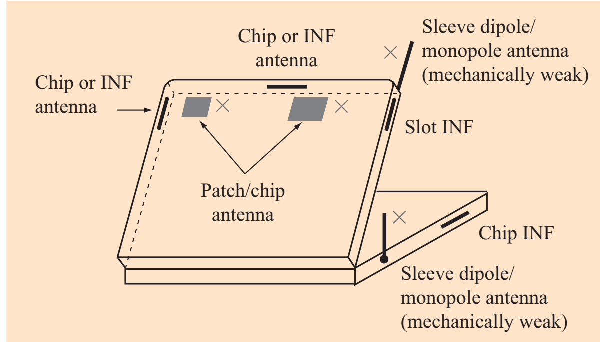

Figure 2

Possible antenna locations for several types of antennas.

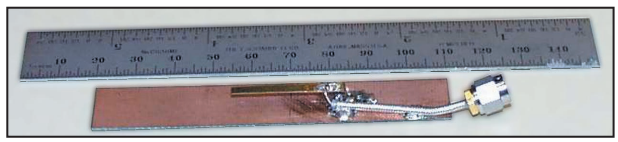

Figure 3

INF antenna used for antenna location evaluations.

Antenna location evaluations

It is very important to have a good understanding of the antenna performance effects due to antenna location. Because of its popularity, an INF antenna (**Figure 3**) was used to examine performance at different locations on a laptop. Since the antenna characteristics are dependent on its location on the laptop, an antenna tuned for a particular location probably will not work as well for other locations. Therefore, some minor modifications to the antenna are necessary to ensure an acceptable standing wave ratio (SWR) in each case. The SWR is defined as

$$SWR = \frac{1 + |\tau|}{1 - |\tau|},$$

where τ is the reflection coefficient for the outgoing wave from the transmitter. No compensation for the shift of the center frequency is made during these evaluations based on the assumption that adjustments for this shift are straightforward. **Figure 4** shows the antenna locations and orientations. Because of laptop symmetry, antenna locations on only the left side of the laptop are considered. The laptop used is an A-Series ThinkPad*, which has acrylonitrile butadiene styrene (ABS) plastic in the display and base covers. Other ThinkPad models use carbon-fiber-reinforced plastic (CFRP, very lossy material at rf frequencies) or metal covers, and the results shown here would not be applicable. **Table 1** lists the peak and average gain values at these locations. In the table, 0° indicates measurements made in the horizontal plane; negative and positive angles indicate measurements made above and below the horizontal plane, respectively. The

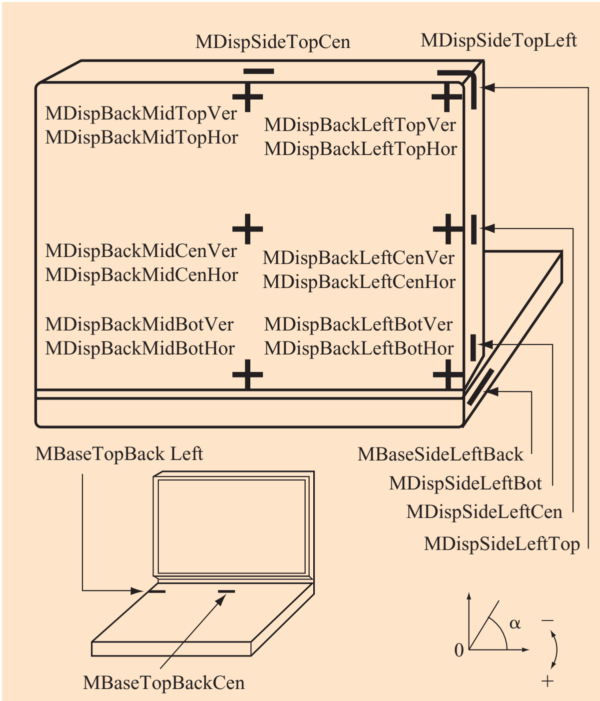

Figure 4

Antenna at laptop display and base.

measurements have an azimuth scan from −180° to 180° and an elevation scan from −40° (above the horizontal plane) to 35° (below the horizontal plane), both in 5° increments. The laptop was open, with an angle between the cover and the base of 90°. Listed in the table are those frequencies corresponding to the maximum average gain value and highest peak gain value. The average gain is defined over an azimuth scan (360°) for a given elevation angle. The table indicates that, except for the MBaseSideLeftBack location, placing the antenna high (center and top) or in vertical orientation tends to yield maximum radiation on or close to the horizontal plane. This is another indication that one should place the antenna as high as possible. **Table 2** lists the center and resonating frequencies and 2:1 SWR of the antenna at different locations. Note that the center frequency, f_{cen}, is slightly different from the resonating frequency, f_{min}. The resonating frequency corresponds to the minimum SWR values. Table 2 indicates that the 2:1 SWR bandwidth will be wider if the antenna is placed on a small ground plane (side of display) or the edge of a large ground plane (back side of display). One must remember that even though the laptop uses a plastic cover, metal foil and shields exist inside the cover to reduce emissions from laptops to meet FCC regulations.

Antenna design methodology

There is always an engineering tradeoff between technical rigor and time to market. Many 3D electromagnetic tools are available for modeling antennas and devices, but even state-of-the-art tools cannot render timely, accurate simulation of this problem. On the other end of the range of design methodologies is the empirical approach: cut, try, and "field-test" in the laboratory. By itself, neither solution is acceptable. A careful balance of the two, with a new test methodology and new evaluation criteria, can provide an acceptable solution. The following sections describe a methodology that has been successfully used to design integrated antennas for laptop computers. There are three parts to the method: modeling, "cut-and-try," and controlled measurement for comparison to specific metrics. While the method is not rigorous in the sense of producing a fully optimized antenna design that is completely characterized, it has proven to be a reasonably efficient technique for finding antenna designs with superior performance in the laptop environment—i.e., highest data throughput, best range, and fewest dead zones.

Modeling

Depending on antenna types and implementation locations on a laptop, 3D antenna-modeling tools can be used. Modeling tools are very important for antenna structures such as patch antennas placed on a laptop display cover. However, simulation results from modeling tools can only be used as a guide for mobile antenna design. Since an antenna radiates, its performance is closely related to its environment. In most cases, modeling tools cannot treat these environments in detail because of geometries and differing computer compositions. Another problem for mobile antennas is the small ground plane. Since the ground plane is small, the mobile device, in this case the laptop, is itself part of the antenna. Therefore, an antenna designed for freestanding operation will generally not work well when the antenna is installed on a laptop. For INF, slot, monopole, and dipole antennas placed on a laptop, cut-and-try design methods together with antenna measurements are more practical and productive approaches.

Cut-and-try

Given the difficulty of modeling the antenna with all of the effects produced by the laptop, it is generally best to develop an antenna design that meets the size constraints imposed by the laptop (as described above). For example, an INF antenna might be modeled and built for use as a freestanding antenna. The next step would be to mount it in the laptop, observe the shift in its performance, and tune it for operation in the laptop environment. Clearly, some metric of the antenna performance is required.

Table 1 Average and peak gain values (frequency in GHz, gain in dBi, angle α in degrees).

Antenna location on laptop	*Horizontal plane α = 0*				*Maximum average*			*Maximum peak*		
	f	*Average*	*f*	*Peak*	α	*f*	*Average*	α	*f*	*Peak*
MdispSideTopCen	2.462	0.08	2.489	3.97	30	2.498	0.44	35	2.492	4.69
MdispSideTopLeft	2.468	−0.37	2.468	4.08	−40	2.489	1.23	−20	2.507	5.10
MdispSideLeftTop	2.600	−1.25	2.519	3.24	10	2.462	1.74	15	2.483	4.78
MdispSideLeftCen	2.480	0.22	2.462	4.07	35	2.447	1.07	35	2.440	5.15
MdispSideLeftBot	2.561	−1.92	2.450	3.49	35	2.444	2.23	35	2.426	5.39
MdispBackLeftTopVer	2.477	−0.94	2.498	3.46	15	2.417	0.67	20	2.417	4.97
MdispBackLeftCenVer	2.423	−0.19	2.426	3.52	−35	2.441	1.25	−40	2.423	4.34
MdispBackLeftBotVer	2.405	−1.57	2.396	3.22	−30	2.417	0.90	−30	2.408	5.50
MdispBackLeftTopHor	2.432	−0.98	2.432	2.49	−10	2.432	0.73	10	2.423	4.92
MdispBackLeftCenHor	2.408	0.39	2.417	5.31	5	2.423	0.85	−25	2.414	6.05
MdispBackLeftBotHor	2.408	−0.86	2.405	6.72	−35	2.453	2.02	10	2.435	6.88
MdispBackMidTopVer	2.441	−0.04	2.444	3.73	10	2.432	0.54	10	2.414	5.37
MdispBackMidCenVer	2.414	0.41	2.402	5.64	−30	2.432	1.46	5	2.417	5.66
MdispBackMidBotVer	2.423	−1.68	2.411	3.02	−35	2.423	−0.64	−35	2.432	4.05
MdispBackMidTopHor	2.354	−0.36	2.342	4.04	10	2.405	0.92	10	2.405	5.85
MdispBackMidCenHor	2.420	0.26	2.426	5.90	−30	2.417	1.01	5	2.420	6.35
MdispBackMidBotHor	2.411	−0.37	2.414	4.97	−40	2.456	2.78	−40	2.450	7.81
MbaseSideLeftBack	2.468	1.65	2.492	6.79	0	2.468	1.65	0	2.492	6.79
MbaseTopBackLeft	2.444	−1.44	2.438	3.40	−30	2.402	1.48	−35	2.405	7.03
MbaseTopBackCen	2.438	−2.62	2.402	1.32	−40	2.429	2.02	−35	2.426	7.08

Note: negative angles for above the horizontal plane

Table 2 Center frequency and SWR values.

Antenna location	*Frequency and bandwidth* (MHz)			*SWR*	
	f_{cen}	f_{min}	*2:1 SWR bandwidth*	SWR_{cen}	SWR_{min}
MdispSideTopCen	2500	2500	164	1.11	1.11
MdispSideTopLeft	2501	2495	154	1.10	1.08
MdispSideLeftTop	2483	2475	166	1.10	1.08
MdispSideLeftCen	2470	2475	164	1.18	1.17
MdispSideLeftBot	2490	2480	147	1.20	1.17
MdispBackLeftTopVer	2437	2435	137	1.19	1.18
MdispBackLeftCenVer	2425	2425	121	1.24	1.24
MdispBackLeftBotVer	2452	2445	142	1.25	1.24
MdispBackLeftTopHor	2445	2440	120	1.05	1.04
MdispBackLeftCenHor	2426	2425	96	1.19	1.18
MdispBackLeftBotHor	2429	2425	119	1.10	1.08
MdispBackMidTopVer	2428	2425	100	1.17	1.16
MdispBackMidCenVer	2427	2425	99	1.17	1.16
MdispBackMidBotVer	2429	2425	97	1.19	1.19
MdispBackMidTopHor	2427	2425	116	1.06	1.06
MdispBackMidCenHor	2422	2420	102	1.17	1.17
MdispBackMidBotHor	2442	2435	117	1.15	1.07
MbaseSideLeftBack	2460	2450	169	1.09	1.03
MbaseTopBackLeft	2416	2410	97	1.16	1.12
MbaseTopBackCen	2441	2440	88	1.09	1.09

Measurements

SWR

Perhaps the most obvious metric is the center frequency and bandwidth of the antenna. These parameters are easy to measure with a network analyzer and provide quick feedback with respect to the effects of the laptop environment on antenna performance and on the tuning process itself. For these applications, the bandwidth is frequently defined as the frequency range over which

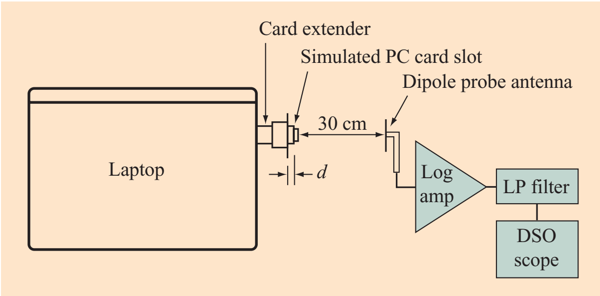

Figure 5

Top view of the PC card test setup (LP = low pass, DSO = digital storage oscilloscope).

SWR <2:1. The goal of the design process is to have the bandwidth of the antenna include the range of the frequency band of the radio plus some margin for antenna manufacture. Since coaxial cables are lossy at 2.4 GHz and more lossy at 5 GHz, one must be careful to understand how this influences SWR measurements on long cables in order to achieve an accurate assessment of performance.

Average gain

SWR is a necessary but not by itself sufficient condition for antenna performance. To obtain another measure of the antenna performance, it is necessary to consider, in more detail, the applications: wireless LAN (WLAN) and Bluetooth. Both are indoor applications with operating ranges between 1 and 100 meters. Under these conditions, the signal at the receiving antenna is the sum of many scattered rays and, in the fringe areas (maximum range) of operation, there may be no dominant ray. In this case, one can assume that the rf propagation environment is described by Rayleigh statistics, which are used later in the link budget description.

From the user's perspective, a good system is one that maintains a reliable high-rate connection throughout the operating range and for any orientation of the laptop computer or position of the user. This requirement alone would argue for an omnidirectional antenna. However, as mentioned above, the received signal at the antenna comes from many different directions, and the details of the antenna pattern are therefore "blurred" by the rf scattering characteristics of the indoor environment. In fact, it can be argued that the most important metric of the antenna, after its center frequency and bandwidth, is its efficiency. That is, if the energy is radiated and not lost, it is a good antenna. Unfortunately, it is difficult to measure antenna efficiency in such conditions.

Another approach and methodology advocated here is to measure the "average" gain of the antenna installed on the laptop in an anechoic chamber (a chamber which simulates a free-space environment). There are numerous ways to define and measure the average gain. The most comprehensive would be to measure the antenna pattern over 4π steradians (all of the radiated energy), average the results over all angles, and normalize the average with respect to an ideal isotropic radiator. In principle, this is straightforward, but in practice it is too tedious. The method used here determines the average gain from pattern measurements made in the horizontal (azimuth) plane for both polarizations of the electric field. The results are averaged over azimuth and elevation angles and normalized with respect to an ideal isotropic radiator. This average gain is used in the link budget model to determine whether the system performance is adequate.

Clearly, this definition of average gain is not a comprehensive or rigorous characterization of the performance of the antenna. It is, however, a measurement which can be performed in a reasonable amount of time and is reproducible, since it is done in an anechoic chamber. In addition, results can be reproduced in different laboratories. It has proved to be a reasonable tradeoff between detailed measurements and the time constraints of developing antenna designs for products.

PC card antenna performance and evaluation

Nearly all laptop computers are equipped with one or two PC card slots for extended applications. Communications-related PC cards, such as the Aironet card, use the slot for the WLAN. The performance of these cards is laptop-dependent. The antenna is placed at the outer end of the card to reduce the effect of the laptop itself on communication performance. Performance is particularly influenced by the effects of metal and the carbon-filled plastic laptop case. Therefore, it is very useful to study signal strength as a function of the spacing between the laptop and the antenna.

The test setup shown in **Figure 5** is for a 2.4-GHz Bluetooth radio subsystem. This experiment is intended to illustrate the effects of antenna placement and laptop materials. One laptop, an IBM 770 ThinkPad, has a popular vendor radio installed in the PC bay using an extender card so that the radio and its antenna are well removed from the conducting surfaces of the laptop. A simulated PC card slot opening fabricated from copper-clad PC board material was placed over the radio. This conducting surface represents shields or conducting plastics used in modern laptops. The card position could be adjusted so that the antenna was outside the slot (positive d displacement), flush with the opening of the slot ($d = 0$ displacement), or inside the slot (negative d displacement). A second radio, installed in another laptop (not shown), was used to form a link and keep the radio under test transmitting. It was located so that its signal at the probe position was much weaker than the signal from the radio under test. The output of the log amplifier, which is proportional to the log of the power received at the probe antenna, was filtered with a low-pass filter and then displayed on an oscilloscope.

The experiment proceeded by setting the distance, d, and measuring the output power of the radio under test. Since the probe antenna was not calibrated, only relative power levels were determined in the measurement. The position of the slot, d, was varied between -10 mm and 15 mm.

The results are shown in **Figure 6** for each of the three possible carrier frequencies used by the radio (2.404 GHz, 2.441 GHz, and 2.459 GHz). The relative output power of the transmitting radio is a function of its antenna position, d, relative to the conducting aperture of the simulated PC card slot. Between -10 mm and $+4$ mm the sensitivity of the output power to this dimension is almost 0.8 dB/mm. The effect saturates at $d = 4$–5 mm. That is, once the antenna is located 4 or 5 mm outside the conducting surface of the laptop, there is little additional benefit to increasing the protrusion of the antenna. It should be noted that the transmitting power was measured only in one direction, which is nearly that of peak gain. Increasing the protrusion further might improve the omnidirectionality of the antenna.

The design of the ThinkPad 770 is indicated by the vertical line on the plot at $d = -2$ mm. The potential for improvement in antenna sensitivity is almost 6 dB if the antenna is moved to a position at which it protrudes 4 mm from the laptop case.

To understand the impact the additional 6 dB has on the link range, consider the following: The radio vendor has reported a range with this radio of 5 m. IBM has developed a link budget model (see the section below) for the Bluetooth radio from which it is possible to determine the range as a function of antenna gain or output. Included in the model is a path loss exponent ($1/r^n$). For indoor environments and short-range applications such as Bluetooth, $n = 2.5$ appears to be a reasonable value, while $n = 3.5$ is used for WLANs. With this model, the 6-dB loss of power when the PC card radio is installed in the 770 reduces the range by more than 40%. If both ends of the link were to have these radios installed in 770s, the range would be expected to be about 1/3 of the case in which the output of the radios is unaffected by the laptops. The reduction in range for the 770, based on the current measurements, is consistent with results reported by the vendor.

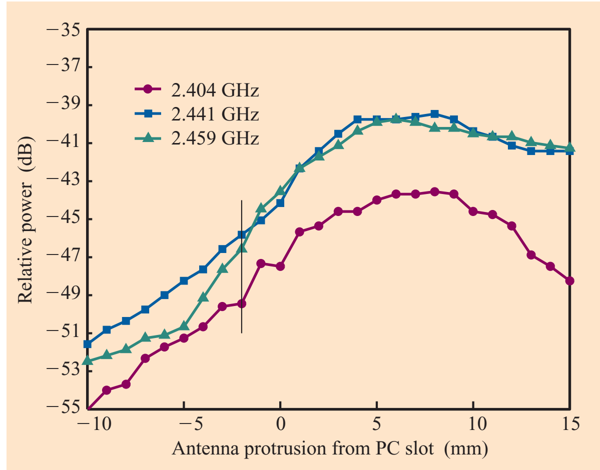

Figure 6

PC card results.

Link budget model

One metric of the performance of a radio system that receives a great deal of attention is its range. Range is often quoted in the advertising of the product. Whether it is a cell phone, a cordless phone, or a WLAN, the user wants the longest possible range while maintaining "good" connectivity. When engineering a single subsystem of a radio, such as the antenna, it is necessary to know how good it has to be. An approach used frequently is to develop a link budget model for the entire radio that can be used to understand the impact on system performance of each of its subsystems. A link budget model calculates the margin in the received signal-to-noise ratio relative to the required signal-to-noise ratio (SNR) for acceptable error rate performance. It is an accounting of the signal power launched by the transmitter, the propagation and antenna losses, and the characteristics of the receiver, such as noise figure and noise bandwidth. In dB, the link margin, LM, can be expressed as

$$LM = (SNR)_{\mathrm{demod}} - (E_{\mathrm{b}}/N_{\mathrm{o}}) = S_{\mathrm{demod}} - N_{\mathrm{demod}} - (E_{\mathrm{b}}/N_{\mathrm{o}}),$$

where $(SNR)_{\mathrm{demod}}$ is the effective signal-to-noise ratio at the demodulator in dB and $E_{\mathrm{b}}/N_{\mathrm{o}}$ is the signal-to-noise ratio required for a low error rate, also in dB.

The signal at the demodulator, S_{demod}, depends on 1) propagation losses and antenna characteristics and 2) receiver implementation. The effects of 1) are described by the Friis transmission formula [10], which gives the power, P_{r}, available at the terminal of the receiving antenna given the power, P_{t}, at the transmitting antenna. It assumes ideal, free-space propagation of an rf signal. P_{r} can be written as

$$P_{\mathrm{r}} = P_{\mathrm{t}} + 10 \log_{10} (\lambda/4\pi r)^2 + G_{\mathrm{t}} + G_{\mathrm{r}} .$$

The separation of the antennas, r, is the range. λ is the rf wavelength. G_{t} and G_{r} are the gain values of the two

Table 3 Example of the link budget spreadsheet.

Parameters	*To access point 11 Mbps*	*Peer to peer at different data rate*			
		11 Mbps	*5.5 Mbps*	*2 Mbps*	*1 Mbps*
Frequency (GHz)	2.45	2.45	2.45	2.45	2.45
Transmit power (W)	0.032	0.020	0.020	0.020	0.020
Transmit power (dBW)	−15.0	−16.9	−16.9	−16.9	−16.9
Transmit antenna gain (dBi)	0.0	−2.0	−2.0	−2.0	−2.0
Polarization loss (dB)	3.0	3.0	3.0	3.0	3.0
EIRP (dBW)	−18.0	−21.9	−21.9	−21.9	−21.9
Range (m)	32.4	25.1	37.3	60.6	90.1
Path loss exponent (dB)	3.5	3.5	3.5	3.5	3.5
Free-space path loss (dB)	88.6	84.7	90.7	98.1	104.1
Rec. antenna gain (dBi)	−2.0	−2.0	−2.0	−2.0	−2.0
Cable loss (dB)	1.9	1.9	1.9	1.9	1.9
Rake equalizer gain (dB)	0.5	0.5	0.5	0.5	0.5
Diversity gain (dB)	5.5	5.5	5.5	5.5	5.5
Receiver noise figure (dB)	13.6	13.6	13.6	13.6	13.6
Data rate (Kbps)	11000	11000	5500	2000	1000
Required Eb/No (dB)	8.0	8.0	5.0	2.0	−1.0
Rayleigh fading (dB)	7.5	7.5	7.5	7.5	7.5
Receiver sensitivity (dBm)	−80.1	−80.1	−86.1	−93.5	−99.5
Signal-to-noise ratio (dB)	8.0	8.0	5.0	2.0	−1.0
Link margin (dB)	0.0	0.0	0.0	0.0	0.0

antennas. The gain of an antenna is given by its radiation pattern and I^2R losses. It is a parameter that is relatively independent of frequency in the band of interest, so that the received power is proportional to the inverse square of the rf frequency. The transmitting antenna is taken to be an access point, with $G_t = 0$ dBi, where dBi is the gain relative to an isotropic radiator.

The term $(\lambda/4\pi r)^2$ is the free-space path loss. It includes a term proportional to $1/r^n$. In free space $n = 2$. However, for indoor office environments there are walls and partitions that attenuate and reflect the signal, which can be accounted for with an effective path loss exponent, $n > 2$. This work uses $n = 3.5$ for WLAN applications, based upon measured impulse channel sounding statistics across a variety of office structures and conditions.

In addition, numerous scatterers affect the rf signal. These have two effects:

1. Each signal reflection tends to randomize the polarization of the electric field, E, with respect to the polarization of the receiving antenna. This effect is included in the model with a polarization loss, PL, of 3 dB.
2. The signal arriving at the receiving antenna is the vector sum of many signals. Since the environment is rarely static, the received signal depends on both position and time. This vector sum, commonly called *fading*, reduces the average value of the signal at the receiving antenna. The loss of signal is accounted for in the model with a Rayleigh fading parameter (RF) of approximately 7 to 8 dB, experimentally determined by impulse channel soundings.

S_{demod} is also affected by the receiver implementation, including the loss, CL, of the cable connecting the antenna to the low-noise amplifier (LNA) of the receiver, and any signal enhancements in the receiver such as equalizer gain, EQ, or diversity gain, DG. S_{demod} can be written as

$$S_{\mathrm{demod}} = P_r - PL - RF - CL + EQ + DG.$$

The noise at the demodulator, N_{demod}, may be written as

$$N_{\mathrm{demod}} = -174 \text{ dBm} + NF + NBW,$$

where NF is the receiver noise figure and NBW is the noise bandwidth of the receiver in dB·Hz.

Through the use of a link budget model and antenna gain measurements made in a controlled environment (e.g., anechoic chamber), it is possible to calculate an "average" range for the system and to understand how different antenna designs affect the range of the system. This method produces reproducible results. However, it should not be treated as equivalent to range measurements in any single environment, only as a statistical representation of what one might expect across a variety of environments. Such measurements are generally characterized by a wide spread in values that stem from the details of the scattering and losses in the propagating environment.

Table 3 shows a link budget in spreadsheet form. In the range calculations, 7.5 dB of extra path loss due to the effects of multipath Rayleigh fading was assumed. Since data is typically sent in packets or blocks, a common system metric used to characterize performance is block error rate. This path loss represents an average power loss due to the effect of destructive multipath summation at the antenna while operating at the 10% block-error rate system sensitivity point. The results shown are the ranges for a laptop to an access point (0-dBi transmitting antenna gain) at an 11-Mb/s data rate and for peer-to-peer laptops (−2 dBi transmitting gain) with different data rates at 11, 5.5, 2, and 1 Mb/s, respectively.

Some examples

INF antenna implementation

Figure 7 shows an INF antenna integrated into a laptop prototype for 2.4-GHz applications. The antenna was stamped from a brass sheet and is mounted on a metal support frame of the laptop display. Since the metal support frame is connected to the laptop display and therefore provides a very large ground plane to the antenna, the antenna system has very stable performance. Thus, even when the feeding coaxial cable is moved around, the antenna input impedance changes very little, a problem that plagues the measurement of even freestanding small antennas with long cables and poor grounds.

Figure 8 shows the measured SWR of the antenna. The vertical dashed lines show the recommended SWR mask for the 2.4-GHz band. Note that the 2.4–2.5-GHz frequency range (slightly wider than the strict U.S. band), is used here to cover worldwide applications. The horizontal dashed line indicates 2:1 SWR. It is clear that the antenna has adequate SWR bandwidth and the maximum SWR is less than 1.6 over the whole band, allowing for manufacturing and environmental margin. It should be noted that the effective cable length in this test is zero, minimizing interpretation and use of this data.

Figure 9 shows the measured radiation patterns of the antenna in the horizontal plane when the laptop is open. The solid and dashed lines are for the horizontal (H) and vertical (V) polarizations, respectively. The dash-dot line is for the total (T) radiation pattern. The gain (average/peak) values are shown in the legend of the figure. The vertical polarization has a gain value larger than

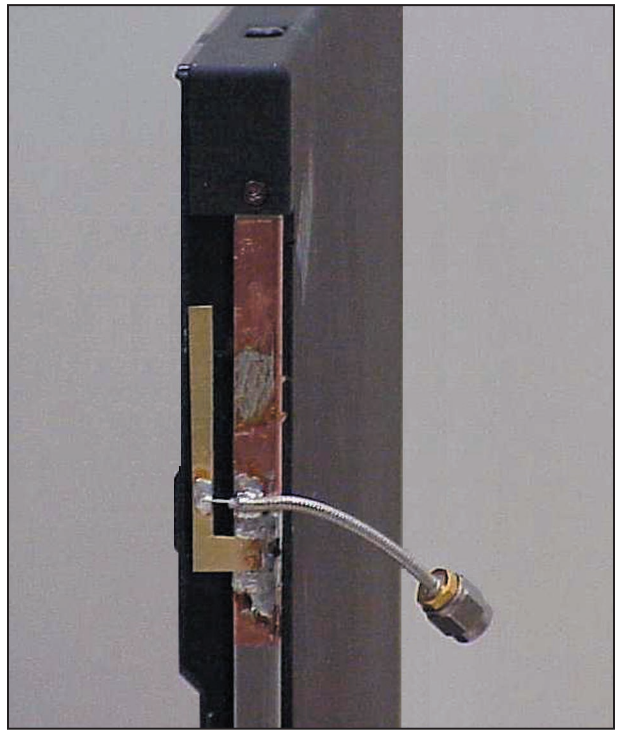

Figure 7

INF antenna integrated in a laptop prototype. Reprinted with permission from [4]; © 2002 IEEE.

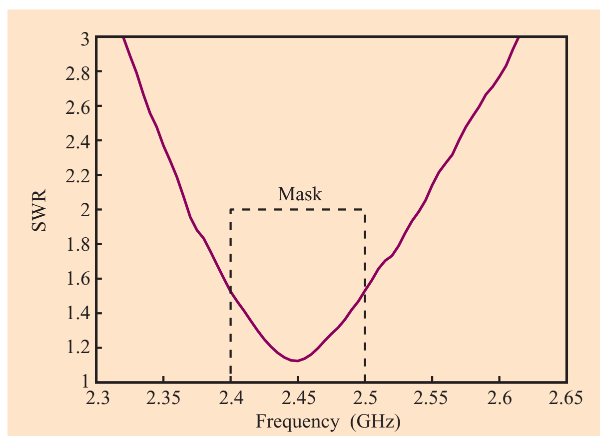

Figure 8

Measured SWR of the integrated laptop antenna in the 2.4-GHz band. Reprinted with permission from [4]; © 2002 IEEE.

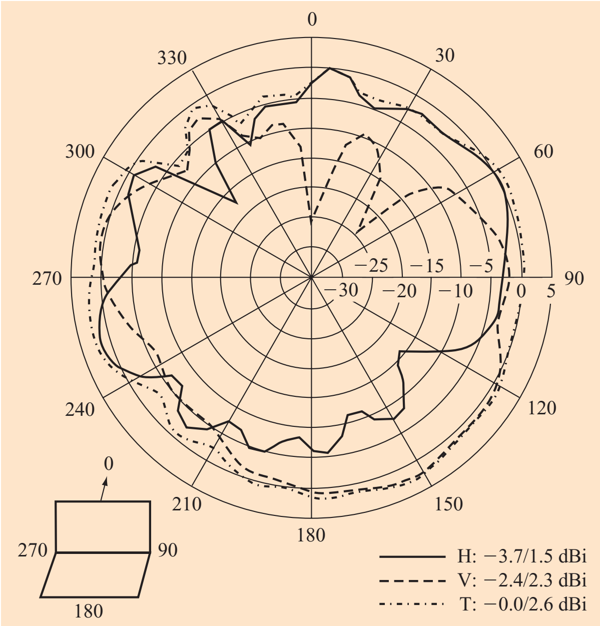

Figure 9

Radiation patterns of the integrated laptop antenna at 2.45 GHz. Reprinted with permission from [4]; © 2002 IEEE.

that of the horizontal polarization. The overall average gain value is about 0 dBi, similar to an isotropic radiator. However, the peak gain value (2.6 dBi) is larger than that of a half-wavelength dipole antenna (2.1 dBi). This is due to the effect of the laptop display surface. In most countries, the peak gain numbers are also important and are tracked by the regulatory bodies creating the need to balance and optimize the average and peak values of each design. For the WLAN case in the U.S., the Federal Communications Commission (FCC) sets a 36-dBm equivalent isotropic radiated power (EIRP) maximum. With a one-watt transmitter output, the maximum peak gain for an antenna is therefore 6 dBi.

The INF antenna is the simplest integrated antenna structure for laptop applications. The antenna can be stamped from a metal sheet, fabricated on a printed circuit board, or cut directly on the metal support structure or the metal foil used for rf shielding. This solution was arrived at through electromagnetic simulation, basic antenna experience, and materials analysis of the laptop plastics and nearby conductors, as well as pre-defined gain and SWR metrics. The SWR and average gain defined above were derived using link budget models that attempt to statistically predict range or coverage in meters at specified throughput or data rates at a given reliability for that connection. The methodology ties the system to the antenna through simulation, empirical testing, and link performance.

Comparison of integrated and PC card solutions

Antenna and wireless system theories indicate that integrated wireless subsystems should outperform the PC card wireless system. Actual measurements for the two wireless systems confirm this conclusion. The IBM iSeries ThinkPad with integrated wireless was used for this study. Two slot antennas were implemented in the ThinkPad, one on the upper left side (vertical) and another on the top right edge (horizontal) of the display. The PC card (IBM High Rate Wireless LAN PC Card) was used for the comparison study. **Table 4** lists the SNR values for distances from 0 to 45 meters with laptop orientation angles 0°, 90°, 180°, and 270°. The SNR values were obtained through the IBM WLAN Client Configuration Utility gain test program. Distances were measured from the access point to the laptop computer. Angle 0 is toward the north from the laptop rear cover, 90° is toward the west (access point direction), 180° is toward the south, and 270° is toward the east. These actual tests indicate that the integrated wireless antenna is 47% better on average than the PC card version. When the laptop is far from the access point, the integrated antenna receives a much stronger signal than the PC card antenna, resulting in much higher SNR. Beyond 25 meters, the SNR for the integrated wireless system is more than 10 dB larger than that for the PC card system. The higher SNR values imply longer distance for the same data rate or higher data rate for the same distance.

As a practical example, an iSeries ThinkPad with the integrated antenna was tested against a PC card version and shown to have superior performance. The test was conducted on the fifth floor of an IBM building in Yamato, Japan. This floor has three access points. When the rf signal was weak, the PC card switched to another access point, while the iSeries integrated antenna performance was still good and maintained a connection to the same access point.

Conclusion

Two performance parameters were used to define integrated antennas for laptop applications. One is SWR, and the other is the average antenna gain. On the basis of link budget models and system requirements, the integrated antennas should have better than a 2:1 SWR bandwidth, wide enough to cover the 2.4-GHz ISM band to ensure a wireless system having a reliable, high-data-rate performance over a useful range or coverage area. The antenna should have average gain values similar to those of an isotropic radiator. The average gain value can be used in a communication link budget model to predict system-level performance such as throughput, reliability,

Table 4 SNR comparison of integrated and PC card wireless solutions.

Distance (m)	*0°*		*90°*		*180°*		*270°*	
	Integrated SNR (dB)	*PC card SNR* (dB)	*Integrated SNR* (dB)	*PC card SNR* (dB)	*Integrated SNR* (dB)	*PC card SNR* (dB)	*Integrated SNR* (dB)	*PC card SNR* (dB)
0	59	54	52	47	54	45	49	49
5	53	50	49	43	49	49	53	50
10	45	37	47	35	45	38	43	36
15	42	31	51	34	46	35	45	26
20	40	22	52	32	45	35	45	26
25	41	33	49	29	43	30	48	22
30	37	21	46	30	43	30	46	24
35	42	22	43	31	42	29	45	20
40	34	23	46	23	42	23	46	27
45	37	29	46	25	42	25	46	28

and range. The antenna polarization is not a critical parameter for laptop applications, since laptops are used primarily in indoor environments where there is high scattering of signals. As one would expect, the best location for integrated antennas in laptops is as high as possible on the laptop display. However, using this location forces a design tradeoff between the antenna's "visibility" and the need for a lossy feed cable, since wireless cards are usually placed in the base of a laptop. The ultimate system cost, time to market, and performance are consciously traded off for each application. No one solution will meet the needs of every laptop, much less every portable device. Current state-of-the-art modeling tools are not accurate predictors of real system performance, but can be used to provide adequate estimates of the design for use with traditional cut-and-try methods.

As expected, the integrated wireless system provides much better performance than the PC card version system. Performance, convenience, and mechanical strength ensure that the integrated wireless will lead the way for the WLAN in the new generations of laptops.

As mentioned in the Introduction, the 5-GHz band provides a data rate of 54 Mbps or more. Future generations of laptops will require integrated antennas for a 5-GHz band as well. A very likely scenario is a laptop supporting both 802.11b and 802.11a wireless LAN technologies. In this case, it is natural to have a dual-band antenna to cover both bands. Moving to the 5-GHz band raises the key issue of cable loss. Since the radio card is usually in the base of a laptop and the antenna is on the top of the display, the feeding cable length tends to be long, more than 50 cm in most implementations. The coaxial cable used for the integrated wireless has a very small diameter (around 1.1 mm) to allow routing through hinges, so the cable has more than 5 dB/m loss at 5 GHz. As a result, the cable loss will be more than 3 dB for the integrated wireless. A loss of 3 dB is very costly from the perspective of wireless performance. Therefore, more studies are needed for the 5-GHz wireless implementation.

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References

1. J. Geier, *Wireless Lans: Implementing Interoperable Networks*, Macmillan Technical Publishing USA, Indianapolis, 1999.
2. J. Bray and C. Sturman, *Bluetooth: Connect Without Cables*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 2000.
3. D. Liu, E. Flint, and B. Gaucher, "Integrated Antennas for ThinkPads—Design and Performance," presented at the Fourth Annual Personal Systems Institute Symposium of IBM, Raleigh, NC, October 17–18, 2000.
4. D. Liu, E. Flint, and B. Gaucher, "Integrated Laptop Antennas—Design and Evaluations," *Proceedings of the IEEE APS International Symposium and URSI Radio Science Meeting*, San Antonio, TX, June 16–21, 2002, Vol. 4, pp. 56–59.

5. Wipro Technologies, "WLAN Glimpse"; see *http://www.wipro.com/prodesign/reusableframeworks/wlan/wlan_glimpse.htm*.
6. A. Huotari, "A Comparison of 802.11a and 802.11b Wireless LAN Standards," The Linksys Group, Inc., May 1, 2002; see *http://www.Linksys.com/products/images/802_11a_vs_802_11b.pdf*.
7. S. H. Wildstrom, "Deluxe Laptops That Work Anywhere," *Business Week*, p. 24, September 17, 2001; see *http://www.businessweek.com/magazine/content/01_38/b3749023.htm*.
8. T. S. Rappaport, *Wireless Communications—Principle and Practice*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1996.
9. C. Soras, M. Karaboikis, G. Tsachtsiris, and V. Makios, "Analysis and Design of an Inverted-F Antenna Printed on a PCMCIA Card for the 2.4 GHz ISM Band," *IEEE Antenn. & Propagat. Mag.* **44,** No. 1, 37–44 (February 2002).
10. C. A. Balanis, *Antenna Theory—Analysis and Design*, Harper & Row Publishers, Inc., New York, 1982.

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