Paper

RADIOFREQUENCY EXPOSURE FROM WIRELESS LANS UTILIZING WI-FI TECHNOLOGY

Kenneth R. Foster*

***Abstract*—This survey measured radiofrequency (RF) fields from wireless local area networks (WLANs) using Wi-Fi technology against a background of RF fields in the environment over the frequency range 75 MHz–3 GHz. A total of 356 measurements were conducted at 55 sites (including private residences, commercial spaces, health care and educational institutions, and other public spaces) in four countries (U.S., France, Germany, Sweden). Measurements were conducted under conditions that would result in the higher end of exposures from such systems. Where possible, measurements were conducted in public spaces as close as practical to the Wi-Fi access points. Additional measurements were conducted at a distance of approximately 1 m from a laptop while it was uploading and downloading large files to the WLAN. This distance was chosen to allow a useful comparison of fields in the far-field of the antenna in the laptop, and give a representative measure of the exposure that a bystander might receive from the laptop. The exposure to the user, particularly if the antenna of the client card were placed against his or her body, would require different measurement techniques beyond the scope of this study. In all cases, the measured Wi-Fi signal levels were very far below international exposure limits (IEEE C95.1-2005 and ICNIRP) and in nearly all cases far below other RF signals in the same environments. An Appendix discusses technical aspects of the IEEE 802.11 standard on which WLANs operate that are relevant to determining the levels of RF energy exposure from WLANs. Important limiting factors are the low operating power of client cards and access points, and the low duty cycle of transmission that normally characterizes their operation.**
Health Phys. 92(3):280–289; 2007

Key words: exposure, radiofrequency; radiofrequency; safety standards; computers

INTRODUCTION

WIRELESS LOCAL area networks (WLANS) are an increasingly common technology employing radiofrequency (RF) energy. A recent press release by a commercial firm reported that there are presently more than 100,000 wireless local-area network "hot spots" in operation around the world.[†] This study concerns WLANs that based on the widely utilized Wi-Fi technology; other technologies such as WiMAX are not considered. The technology has occasionally prompted questions from the public about health and safety issues related to exposure to RF energy, and in U.K. schools, WLANs have been removed due to health concerns (Bale 2006).

While WLANs clearly operate at low power, little quantitative information is available to the public or to health physicists and other professionals about the levels of exposure that they produce to the public. A few technical reports have recently appeared (e.g., Schmid et al. 2005), but little if anything is presently available in the conventional scientific literature. This study reports a survey of RF fields associated with WLAN technologies and other environmental sources of RF energy in a variety of locations that are typical of those that might be accessible to the general public. An Appendix provides more detailed considerations related to RF exposure from WLANs.

Almost all WLANs are based on the IEEE 802.11 standard and one of its amendments (IEEE 1999; Williamson 2004; O'Hara and Petrick 2005). The technology is popularly known by the (trademarked) name Wi-Fi and is supported by an industry group, the Wi-Fi Alliance. In a typical case (called an infrastructure network), a wireless network adapter (alternatively known as client card) in a user's computer communicates with an access point (AP, alternatively known as a wireless router, wireless gateway, or base station) that provides connectivity with a network infrastructure that may include wired and wireless devices. Wi-Fi technology has been widely adopted by consumers and business, and Wi-Fi "hot spots" are found in many coffee houses, airports, train stations and other heavily traveled areas throughout the world, as well as in a great many homes of individual users.

* Department of Bioengineering, University of Pennsylvania, Philadelphia, PA 19104.

For correspondence contact the author at the above address, or email at kfoster@seas.upenn.edu.

(*Manuscript accepted* 9 *September* 2006)

0017-9078/07/0

[†] http://www.jiwire.com/press-100k-hotspots.htm.

Wi-Fi technology utilizes an unlicensed spectrum at 2,400–2,483.5 MHz in many parts of the world[‡] (2,412–2,462 MHz in the U.S.). This is part of the industrial-scientific-medical (ISM) band of 2.4–2.5 GHz that is used for many other purposes including Bluetooth wireless interfaces, microwave ovens, a variety of unlicensed wireless devices such as cordless telephones, and industrial heating and medical appliances. A newer version of the 802.11 standard, 802.11a, uses unlicensed bands at 5.15–5.35, 5.47–5.725, and 5.725–5.825 GHz (in the U.S.), but is not widely deployed at present. (The present study considered only WLANS operating in the 2.4 GHz band.)

The Appendix summarizes technical information about the 802.11 standard that is relevant to RF exposure to the user. In brief, Wi-Fi networks transmit bursts of RF energy encoded using one of several modulation schemes, using channels that are 22 MHz wide in the 2.4 GHz band. Client cards and APs operate at roughly similar powers, typically with peak power levels below 100 mW (although some devices operate at peak levels up to 1 W) using low-gain antennas. Access points may be located tens of meters from the user or on a desk near the user's computer. Client cards are installed in the user's computer. At any given location, the total RF signal present from a WLAN is a combination of that from the AP and client card, with the closest source (usually, the client card in the computer) usually providing the major contribution to the signal.

The present study, supported by the Wi-Fi Alliance, was intended as a broad survey of RF fields associated with WLANs in diverse locations, both residential and commercial, in four countries (the U.S., France, Germany, Sweden). The aim was to sample RF signals associated with WLANs against a background of RF fields present from other environmental sources in diverse locations that are typical of settings in which consumers or office workers might be present. The locations were chosen in part as a matter of convenience (to accommodate travel plans of the author) and in part to benefit from assistance of employees of member firms of the Wi-Fi Alliance to help with local arrangements. Essentially the same equipment from a handful of vendors is used in WLANs throughout the world, and (apart from minor variations in frequency range) the field levels experienced by the user would be similar. However, the RF environment in different countries can be expected to vary, if only because the frequencies used by mobile telephone systems and other wireless communications technologies vary somewhat across the globe, and it was thought to be useful to sample WLAN fields in several different countries.

The goal of this study was to obtain a representative set of measurements of RF fields that a user of a WLAN might experience in a variety of settings from ordinary life. No attempt was made to provide a statistically valid sample of RF energy from WLANs in all environments in which a person might be located, however that may be defined. The overwhelming fraction of measurements were in indoor locations where WLANs were known to be present, and sites were chosen where possible to be close to access points. Most of the chosen locations were indoors, frequently in suburban locations. This differs from an earlier survey by Tell and Mantiply (1980) that measured RF fields at numerous outdoor sites in major U.S. cities.

MATERIALS AND METHODS

RF field measurements

Radiofrequency fields were measured using a Narda SRM-3000 selective radiation meter (Narda Safety Test Solutions, 435 Moreland Road, Hauppauge, NY 11788 USA). This instrument is a portable spectrum analyzer that covers the range 75 MHz–3 GHz with high sensitivity, equipped with an isotropic (three-axis) antenna. The instrument calculates the power spectrum of the signal (averaged over the three axes of the antenna) using the Fast Fourier Transform and stores the data for subsequent export to a computer. For the present measurements, spectra were stored as running averages of 64 sweeps, with a sweep time of 0.6–1.9 s per spectrum (depending on the frequency range). Consequently, the field measurements reported below are averages over periods ranging from approximately 40 to 120 s. This is much shorter than the "averaging time" mentioned in IEEE C95.1 (2005) and ICNIRP (1998) exposure limits (6 min and 30 min) but much longer than the time between pulses from the WLANs. No attempt was made to measure 6- or 30-min average exposures, which would be required by compliance testing; in view of the low field intensities the issue of compliance is moot in any event.

Measurements were conducted over the maximum frequency range of the instrument, 75 MHz–3 GHz, to allow a measurement of WLAN signals in comparison with the background electromagnetic environment in the radiofrequency region. Measurements were conducted with the smallest resolution bandwidth (RBW) provided by the instrument for that bandwidth, 1 MHz. Additional measurements were taken over the band used for Wi-Fi in the U.S. (2.4–2.473 MHz) with RBW of 30 kHz, sweep time of approximately 0.9 s, to provide a finer

‡ http://www.atheros.com/pt/whitepapers/Atheros_Regulatory_whitepaper.pdf.

display of the WLAN signal. All measurements were performed at the highest sensitivity available with the instrument, with a full scale range of 1.6 μW cm^{-2}, averaging 64 sweeps. This provided a noise floor of about 10^{-7} W m^{-2}, which is remarkable given the small size and portability of the instrument.

The Narda meter measures RF energy whatever the source. However, the sources of the measured signals could often be identified due to the use of a small resolution bandwidth and the spectral characteristics of the signals. For example, WLANs operating on different channels could be identified by their distinctive bandwidths, but different WLANS utilizing the same channel could not be resolved. In a few cases other sources of RF fields in the ISM band were observed, which could be identified by the spectral characteristics of the signal and presence of nearby equipment, e.g., a nearby microwave oven.

Network analysis

Two software packages were used to identify and characterize WLANs. Observer (Network Instruments, Minnetonka, MN) was used to identify active networks and access points and to measure signal strengths of WLANs. The program also measures the bandwidth and interface utilizations of the network. These parameters are useful to judge the capacity of the network but, unfortunately, are difficult to interpret in terms of the fraction of time that an AP or client card is transmitting (which is the quantity of dosimetric interest).

In addition, a network "sniffer" program (NetStumbler, http://www.netstumbler.com/) was used with either a Netgear client card (Model WG511U, Netgear, Inc., Santa Clara, CA) or the internal client card in the laptop (a RaLink 2500 series miniPCI card). NetStumbler is principally used to identify WLANs and determine signal strength but provides no information about clients that might be communicating with the WLANs. Both Observer and NetStumbler use the internal circuitry of the client card to measure the signal strengths of WLANs, which is helpful in supplementing data provided by the Narda probe (total RF power over a given frequency range). Observer (but not NetStumbler) configures the client card to operate in the promiscuous (receive-only) mode, which prevents it from contributing to the total RF signal measured in the vicinity of the laptop by the Narda probe.

Location of measurements

A total of 356 measurements were conducted at 55 sites in Europe and the U.S. (Table 1).

At each site, environmental RF fields were measured using the Narda meter; in addition, Observer and/or NetStumbler were used to identify active networks and estimate bandwidth utilization.

Several different measurement protocols were employed. For one set of measurements (243 individual measurements), the Narda instrument was used to record RF signals in the environment with the client card of the laptop either disabled or connected to the WLAN but not transmitting data. For a number of these measurements, an access point could be identified protruding from the ceiling or mounted on a wall, and measurements were made as close as practical to the AP, usually by holding the meter at waist height while standing near the AP. In other cases, typically in coffee shops or other commercial spaces, no APs were visible and measurements were made in a convenient location. In the second set of measurements, the laptop (an Averetec 3200 series computer) was connected to the WLAN and used to upload or download large files to the network, in most cases to and from an ftp site in Philadelphia but in other cases to a local network near the site of the measurements. In a few cases, streaming media files were also downloaded to the laptop. In a third set of measurements, RF measurements were conducted with the Narda probe at different distances from the laptop while uploading and downloading large files to the network.

Table 1. Location of measurements.

Location of measurements	Locations/ total number of measurements	Total number of measurements (number of different sites)
Hospitals/health care facilities, universities	(Stockholm, Detroit MI, Philadelphia PA)	64 (4)
Commercial locations (coffee shops, fast food outlets, general merchants), tourist visitor center	Stockholm, Wiesbaden (Germany), Manchester VT, Philadelphia PA and surrounding area	98 (35)
Homes, hotel rooms	Paris, Philadelphia PA and surrounding area; Stockholm, Uppsala (Sweden)	78 (6)
Office areas	San Jose CA, Seattle WA, Vélizy (suburb of Paris), Kiska (suburb of Stockholm)	75 (4)
Other (train stations, outdoor environments)	Stockholm, Paris, Philadelphia	41 (6)

Data analysis

The data stored in the Narda, which consisted of arrays of power density values together with instrumental settings, were exported to a computer and analyzed using routines written in Matlab (Mathworks, Natick MA). Because the RBW of the measurements were much smaller than the width of the channels used by WLANs (22 MHz), much less the total range of frequencies employed by Wi-Fi networks, it was necessary to integrate the power density readings over an appropriate bandwidth. The integrated power density $S_{integrated}$ was calculated using a formula provided by Narda:[§]

$$S_{integrated} = \sum_i \frac{S_i}{1.055 RBW} \Delta f = 0.47 \sum_i S_i, \quad (1)$$

where S_i is the power density of the i^{th} spectral component stored by the instrument and Δf (= RBW/2) is the frequency spacing between stored spectral components. In eqn (1), the sum runs over all data points within the frequency range of interest. This formula (which is not documented in the manufacturer's manual for the instrument) was tested by inputting a calibrated broadband signal (from a Yokogawa VC200 WCDMA digital radio tester, Yokogawa Electric Corp., Tokyo, Japan) and comparing the integrated power density calculated over a wide bandwidth using internal integration routines in the Narda meter and from the exported data using eqn (1).**

To provide a measure of the total RF power density in the band used by WLANs, the integrated power was calculated from 2,400–2,484 MHz. No attempt was made to isolate WLAN signals from other sources of RF energy in this band. Indeed, in a few cases other sources contributed noticeably to the integrated RF power, including in one case a microwave oven operating in an adjacent room, and in another case a portable telephone on a desk a few meters from the Narda instrument. The integrated RF power over the entire range of the instrument, 70–3,000 MHz, was also computed using eqn (1).

In calculating the integrated power density, it was necessary to remove the baseline noise, which otherwise would have contributed significantly to the sum in eqn (1). For the integrations over the ISM band, the baseline was determined by linear interpolation of data just below and just above the band. To remove the baseline from the broadband measurements, a nonlinear filter was created to isolate the significant peaks in the spectrum. A template was constructed by adding the absolute values of the first and second derivatives of the spectrum, and thresholding the result to a value of 1 where the function exceeded approximately twice the baseline level, and zero otherwise. This template was then multiplied by the spectrum, and the result integrated using eqn (1). While this undoubtedly missed some of the smaller peaks in the spectrum, these would have contributed negligibly to the integrated RF power. In all cases, the plots of the spectra were inspected during the analysis to verify the procedure.

§ Information supplied by C. Eskerski, NARDA Safety Test Solutions GmbH.

** These measurements were performed by Lennart Hamberg, Ericsson, Kiska Sweden.

RESULTS

The measurements showed, as expected, RF signals in the environment from a variety of broadcast and communications applications. Nearly all of the sites had multiple WLANs, many operating on the same channel, each with multiple clients communicating with them. The signal from most of these networks was usable by the client card, but far too small to be measured by the Narda meter. In nearly all cases, the field intensities within the band used by WLANs were exceeded by other RF sources.

Figs. 1, 2, and 3 show three representative results: in a train station in Paris directly beneath an AP located on a beam overhead; from an office/medical treatment area on the fifth floor of a building in Detroit, near a window

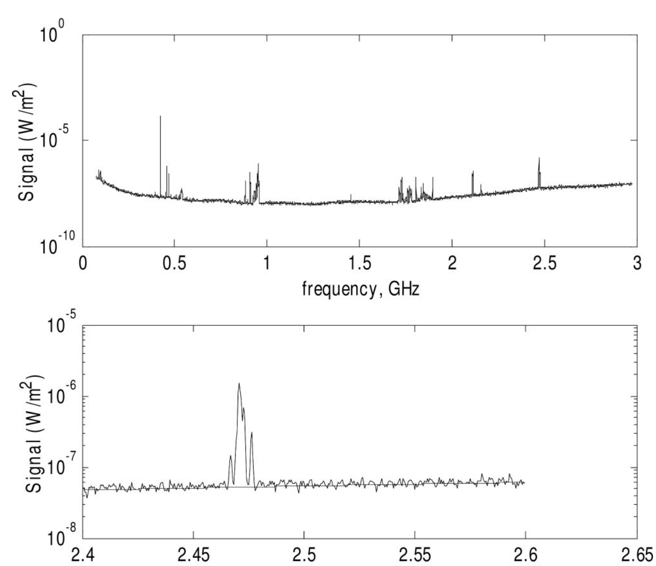

Fig. 1. RF power density measured in the train platform area of a railroad station (Gare de Lyon, Paris); the AP was located on a beam approximately 2 m above the Narda meter. The client card of the laptop was disabled. The bottom panel is an expanded view of the WLAN signal. Peaks around 0.9 and 1.8 GHz are from wireless base stations and that near 0.5 GHz is a UHF television signal. The baseline removed from the WLAN signal is shown by the straight line.

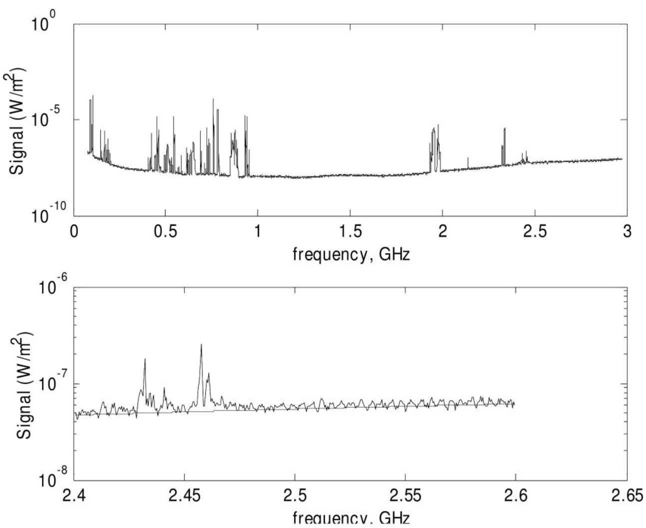

Fig. 2. RF power density measured on fifth floor of a Detroit office/medical practice building. The signal at 2.45 GHz is from an AP located approximately 5 m from the Narda probe and in a different room of the building. The strong peaks are from cellular base stations (850 MHz and 1.9 GHz), and from a variety of broadcast and communications signals below 800 MHz. The bottom panel shows an expanded scan of the WLAN signal. For these measurements, the client card of laptop was disabled. The baseline removed from the WLAN signal is shown by the straight line.

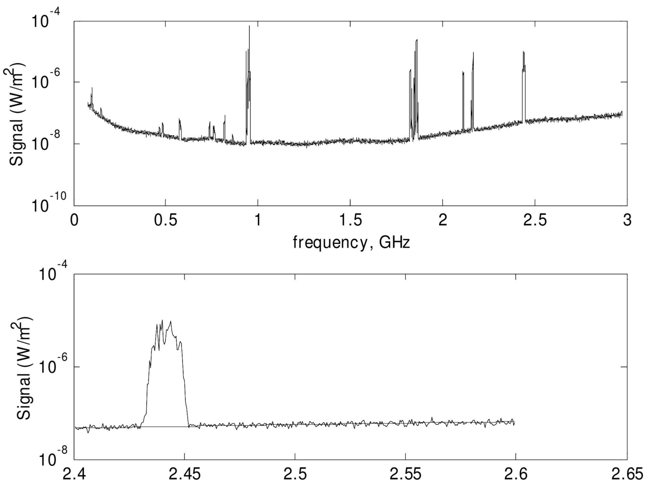

Fig. 3. RF power density measured approximately 1 m from laptop while uploading a large file to a ftp site (Wiesbaden, Germany). The bottom panel is an expanded view of the WLAN signal. The strong peaks at 0.9, 1.8, and 2.2 GHz are wireless telephone signals (GSM 900, GSM 1800, and UMTS, respectively). The baseline removed from the WLAN signal is shown by the straight line.

overlooking the center of the city; and in a hotel room in Wiesbaden, Germany, in a room that overlooked the street approximately 20 m from a wireless base station on the roof of the opposite building, while uploading a large file to an ftp site located in Philadelphia.

Fig. 4 shows a cumulative distribution of RF field intensities in the band used by WLANs, and also over the entire range of the instrument. The median values of the RF field intensities in the band used by WLANs (2,400–2,483.5 MHz) were approximately 10^{-6} W m^{-2} at distances of 1 m or more from the laptop when its client card was not transferring files. At a distance of about 1 m from the laptop when it was uploading or downloading large files, the median power density was about a factor of 10 higher.

Fig. 5 shows one series of measurements of RF fields from the WLAN at varying distances from a laptop while it was uploading or downloading large files to the WLAN. These measurements were done in a hotel room in Wiesbaden, Germany, and the files were being uploaded to an ftp server in Philadelphia; a scan over the entire spectrum is shown in Fig. 3. The RF power density falls off as the inverse square of the distance from the computer, indicating that the majority of the signal originated from the client card (as opposed to the AP). For comparison, the figure also shows the power density in the main beam, calculated for a dipole antenna radiating 33 mW, which is the rated output of the client card in the computer. The measured power densities (which reflect averages over times of about 1 s) are an order of magnitude or more smaller than calculated at a similar distance for a dipole antenna driven at the rated power of the client card, indicating a low duty cycle of transmission. Presumably the large variability in the

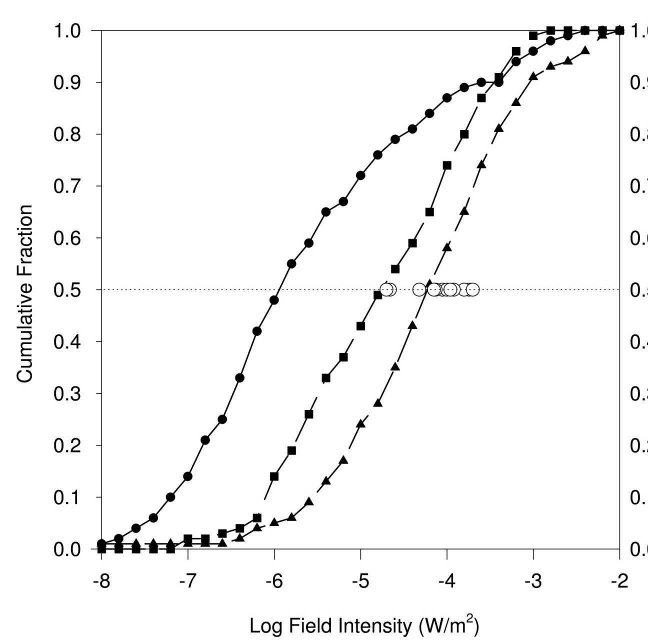

Fig. 4. Cumulative distribution of power density. (●) 2.4–2.48 GHz, client card not communicating with network; (■) client card communicating with network, 2.4–2.48 GHz; (▲) 70–3000 MHz; (○) median fields in U.S. cities (Tell and Mantiply 1980).

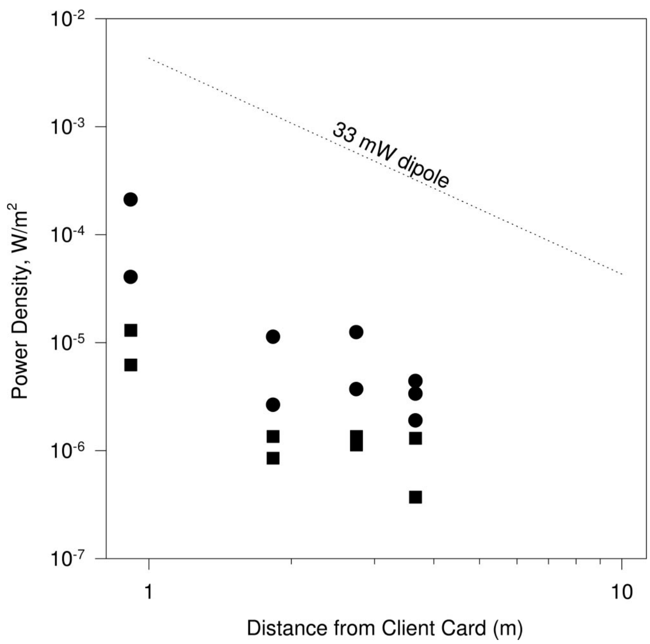

Fig. 5. RF fields in Wi-Fi band measured at different distances from the client card in the laptop, while uploading (●) and downloading (■) large files to an ftp server. Also shown is the field pattern from a dipole antenna transmitting the same power as that of the client card of the laptop.

measured power density is due to fluctuations in the rate of transmission of information from the computer.

DISCUSSION

All of the fields measured in this study were far below international exposure limits (Table 2). This is expected, in view of the low power of the sources and the fact that all measurements on WLANs were made approximately 1 m or more from the AP or client card.

Curiously, the median power density, integrated over the entire frequency range of the Narda meter, was close to the center of the range of median power densities measured between 50–900 MHz in 15 U.S. cities in 1980 by Tell and Mantiply (1980) (Fig. 4). The dominant sources of RF energy reported in that study were typically UHF television broadcasting facilities. These transmitters are still present, together with many new sources from wireless communications systems. One would expect that RF field levels in urban environments would be somewhat higher than those reported in the 1980 study. However, there were important differences between the two studies. Tell and Mantiply (1980) conducted their measurements in outdoor locations in central city locations, while most of the present measurements were conducted indoors, typically in suburban locations.

All of the present measurements were conducted at distances of approximately 1 m or more from the client card in a laptop computer. They are representative of the field intensities in the far field close to a laptop. The user of a laptop would be exposed to stronger fields than reported here, particularly if the antenna in the client card were close to the user's body. No attempt was made in this study to assess near-field exposures to a user of the laptop itself. The Appendix discusses some considerations related to near-field exposure from client cards.

The major finding of this study, that RF fields from WLANs in typical environments are far below exposure guidelines and in nearly all cases below other RF signals that are present in the same environments, is clearly established. As a survey of WLAN fields in the environment, this study has limitations that need to be pointed out. The measurement locations were chosen as a matter of convenience, not to provide a statistically valid sample of the environments (however that may be defined). In particular, the signals from WLAN access points are usable by clients over distances of tens of meters from the AP, but (particularly in lightly loaded networks) at that distance would

Table 2. Comparison of measured RF fields in frequency range used by IEEE 802.11 WLANs (2.4–2.483 GHz) with IEEE and ICNIRP exposure limits.

Measurement 2.4–2.48 GHz	Maximum time-averaged power density, 2.4 GHz band, W m^{-2}	Median time-averaged power density, W m^{-2} (from Fig. 4)
Integrated power density, 2,400–2,483 MHz, laptop not communicating with the WLAN (may include other ISM band sources)	7×10^{-3}	1.2×10^{-6}
Laptop uploading/downloading file, measured approximately 1 m from client card	1×10^{-3}	1.6×10^{-5}
Integrated power density, 70–3,000 MHz	4×10^{-2}	6×10^{-5}
	Exposure limit, W m^{-2}	
IEEE C95.1-2005 (2005) (uncontrolled exposure, equivalent to general public), ISM band	10 (averaged over 30 min)	
ICNIRP (1998) (general public), ISM band	10 (averaged over 6 min)	

be too small to measure with the Narda meter. Consequently, the measurements were biased towards the high end of RF signals from WLANs. If there were a scientific need to obtain a statistically valid sample of all WLAN fields in the environment, that would require a study of different design than the present survey. Given the technical complexities that underlie WLAN networks (Appendix), that might be a difficult task. Given the low level of exposure to people from WLANs in comparison to other sources of RF energy that are ubiquitous in modern environment, any health concerns would seem to be moot.

Acknowledgments— This work was supported by the Wi-Fi Alliance.

REFERENCES

Bale J. Health fears lead schools to dismantle wireless networks. The Times (London); 20 November 2006.

Haratcherev I, Taal J, Langendoen K, Lagendijk R, Sips H. Automatic IEEE 802.11 rate control for streaming applications. Wireless Comm Mob Comput 5:421–437; 2005.

IEEE. IEEE Std 802.11 and various amendments. Piscataway, NJ: The Institute of Electrical and Electronics Engineers, Inc.; 1999.

IEEE. IEEE Std C95.1-2005. IEEE Standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz. Piscataway, NJ: The Institute of Electrical and Electronics Engineers, Inc.; 2005.

International Commission on Non-Ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys 74:494–522; 1998.

Kühn S, Lott U, Kramer A, Kuster N. Assessment of human exposure to electromagnetic radiation from wireless devices in home and office environments. In: Proceedings of the WHO Workshop on Base Stations & Wireless Networks: Exposure and Health Consequences [online], 15 June 2005, Geneva. Available at http://www.who.int/peh-emf/meetings/archive/bsw_kuster.pdf.

O'Hara B, Petrick A. The IEEE 802.11 haandbook: a designer's companion. Piscataway, NJ: IEEE Press; 2005.

Schmid G, Lager D, Preiner P, Überbacher R, Neubauer G, Cecil S. Bestimmung der Exposition bei Verwendung kabelloser Übermittlungsverfahren in Haushalt und Büro. Bonn, Germany: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit; 2005 (in German). Available at http://www.bmu.de/files/strahlenschutz/schriftenreihe_reaktorsicherheit_strahlenschutz/application/pdf/schriftenreihe_rs669.pdf. Accessed 9 January 2007.

Tell RA, Mantiply ED. Population exposure to VHF and UHF broadcast radiation in the United States. Proc IEEE 68:6–12; 1980.

Williamson C. Wireless internet: protocols and performance. Lecture Notes Computer Sci 2965:118–142; 2004.

APPENDIX[††]

Considerations Related to Human Exposure to RF Energy from WLANs

This appendix provides a more technical discussion of factors that determine human exposure to RF energy from WLANs. The present discussion pertains to WLANs based on IEEE 802.11b,g standards (popularly known as Wi-Fi). Other wireless network technologies are based on IEEE 802.16a (WiMAX) and IEEE 802.20 (Mobile Broadband Wireless Access or MBWA), for which similar considerations would apply.

Frequency and modulation

Wi-Fi devices operate within one of two frequency bands, depending on which part of the IEEE 802.11 standard is being implemented, with minor variations depending on region. In most of the world, WLANs operate at 2.4–2.4835 GHz; a newer and presently not widely used band is 5.15–5.725 GHz (5.15–5.825 GHz in the U.S.) (Table A1).

Within these bands, WLANs use radio links between an access point (AP) and client card. The signal is transmitted in the form of packets of variable duration, using channels of 22 MHz bandwidth. Each packet is encoded with bits using a modulation scheme that depends on the particular standard that is being implemented.

Factors that determine exposure levels from APs and client cards

Several factors determine the level of exposure that a person will receive from APs and client cards.

Power output of card. The maximum power output of client cards and APs is specified by national regulatory bodies. In the U.S., regulatory limits (of the Federal Communications Commission, FCC) are specified in terms of the maximum transmitter power output (TPO), while those in Europe and most other parts of the world are in terms of maximum isotropic radiated power (EIRP). Ignoring antenna cable losses, the EIRP is the product of the TPO with the antenna gain. In the 2.4 GHz band, the European limits are 100 mW for EIRP; U.S. limits correspond to an EIRP of 1 W. Limits in the 5 GHz band vary in different subregions of the band but range up to an EIRP of 1 W.

In practice, client cards used with portable computers normally operate at lower power levels than regulatory limits to conserve battery power. For example, the laptop used in this study (an Averatec 3200, Averatec, Santa Ana,

[††] Appendix co-authored by K. Foster and J. Wiart (Joe Wiart, France Telecom RD, RESA, FACE, IOP, 38-40 Rue Gen Leclerc, Issy Les Moulineaux, F-92794, France).

Table A1. IEEE 802.11 standards.

	802.11b	802.11g	802.11a
Max. speed (bps, millions of bits per second)	11 Mbps	54 Mbps	54 Mbps
Modulation	CCK (complementary code keying)	OFDM (orthogonal frequency division multiplexing) & CCK	OFDM
Frequencies	2.4–2.4835 GHz	2.4–2.4835 GHz	5.15–5.825 GHz (U.S.) 5.15–5.725 GHz (Europe)

CA) had a built-in client card with a TPO of 33 mW; a second client card (Netgear model WG511U, Netgear, Inc., Santa Clara, CA) allowed the user to set the TPO in several steps from 10–100 mW). Unlike mobile phone handsets, client cards do not employ adaptive power control, which is used with mobile phone handsets to reduce the power to minimum levels needed to maintain quality service (to conserve battery power), although that possibility exists within the IEEE 802.11 standard.

Thus, the peak power output of APs and client cards is comparable to or somewhat below those of mobile telephone handsets, which operate at TPOs in the range of 100–500 mW. If the antenna of a client card is placed against the body, the absorbed power in the body (measured in terms of specific absorption rate or SAR) will be comparable to that produced by a mobile phone handset. Kühn et al. (2005) reported measurements of SARs produced by client cards in "phantom" models of the body. The cards had been modified to transmit at essentially 100% duty cycle, and their antennas were placed in direct contact with the models. Under these conditions (which are unrealistic in terms of actual usage of the devices), the SAR levels from some of the client cards approached regulatory limits for partial-body exposure.

Antenna gain. Antenna gain, or equivalently the beam pattern of the antenna, is a second major factor. The power density S (Watt m^{-2}) produced at distance r from an antenna with gain function $G(\theta,\phi)$ that is transmitting power P is given by the Friis transmission formula

$$S(r,\theta,\phi) = \frac{PG(\theta,\phi)}{4\pi r^2}, \qquad \text{(A1)}$$

where (θ,ϕ) are the angles between the forward direction of the antenna and the point of measurement. Client cards and APs normally use low-gain antennas, typically with maximum gains ranging from 1 to 2, and regulatory bodies generally require that the power output be reduced if high-gain antennas are employed. {There are exceptions, however. In the United States, FCC regulations [FCC Part 15.247 (b) (4) (ii)] state that "Systems operating in the 5725–5850 MHz band that are used exclusively for fixed, point-to-point operations may employ transmitting antennas with directional gain greater than 6 dBi without any corresponding reduction in transmitter peak output power."} Consequently, the signal at a given distance from the antenna will depend on the angle of observation but generally falls off as the square of the distance from the antenna. In indoor environments, the strength of the signal will vary considerably from the free-space values at the same distance because of multiple reflections from walls and other objects.

Duty cycle of transmission. The IEEE and ICNIRP exposure limits for RF energy are stated in terms of power density averaged over 6 or 30 min. However, WLANs transmit brief pulses of RF energy, and the duty cycle of transmission of both the AP and client card (i.e. the fraction of time the source is transmitting) is ordinarily very low. The (time-averaged) exposure they produce is consequently far below that which would be produced by a continuous source operating at the same peak power level.

In practice, a number of factors determine the duty cycle of transmission. The minimum duty cycle of transmission by an AP is set by the periodic management packets (called beacon signals) that it transmits. Most WLANs are configured to transmit beacon signals, to alert clients within range of the existence of the AP, that consist of short (a few tens of microseconds) pulses, repeated at a rate of 10 s^{-1}. This corresponds to a duty cycle of transmission about 0.01% from the AP.

The duty cycle will increase when a user transmits data to the WLAN. Ordinary activities of a user (reading email or surfing the Internet) represent only a tiny fraction of the capacity of the WLAN and, consequently, only a tiny increase in the fraction of time that the network is transmitting data.

The exact increase in duty cycle, however, depends on a number of factors. One important factor is the rate of data transmission (which varies with the version of the IEEE 802.11 standard that is being used). A faster data transmission rate will result in shorter transmission times and thus lower duty cycles for the AP and client card. In its original form, the IEEE 802.11 standard specified data rates at either 1 or 2 Mbps (million bits per second). In 1999, the IEEE defined two high rate extensions: 802.11b with data rates up to 11 Mbps in the 2.4 GHz band, and 802.11a with data rates up to 54 Mbps in the 5 GHz band. In 2003, the IEEE finalized yet another version of the standard, 802.11g, which supports data rates up to 54 Mbps in the 2.4 GHz band. Obviously, a faster data rate means shorter transmission times and correspondingly lower exposures to the user.

A second factor that determines the duty cycle is the signal quality. If the signal is degraded (from fading due to multiple reflections and diffraction, attenuation due to the distance from the client card to AP, or from interference from other radiation sources), the error rate of transmission will increase. The network adapts by retransmission of packets that have been lost or corrupted, by using a lower data transmission rate, and by reducing the number of bits transmitted in each packet. All of these factors will tend to increase the duty cycle of transmission of both the AP and client card (Haratcherev et al. 2005).

A third factor that determines duty cycle is the presence of other APs and clients using the same channel. The 802.11 group of standards specifies collision avoidance protocols that ensure that only one transmitter (an AP or client card) is active at a time; if a number of APs and client cards are set to use the same channel, the transmission rate of all of the WLANs sharing the channel will suffer. Using the network analyzer program in this survey, each site was typically found to have multiple APs using the same channel, each communicating with multiple clients. Only one of these devices (a single AP or a single client card) can transmit at any given time. This, obviously, reduces the maximum duty cycle of transmission of any device. In practice, an AP that is supporting multiple client cards will have a higher duty cycle of transmission than any client card.

A fourth factor is the capacity of the hardwired network to which the WLAN connects. The effective rate of data transfer between the client card and the WLAN (and hence the duty cycle of transmission from each) may be limited by bottlenecks in the hardwired network, rather than by the transmission rate between the AP and client card. Thus, for example, in the experiment in this survey in which a file was uploaded from Germany to an ftp site in Philadelphia (Fig. 5), the transmission rate of the network was apparently limited by a slow rate of transfer of data between Europe and the U.S., and the duty cycle of transmission of the client card in the computer was quite low. Repeating the same experiment in the same institution in Philadelphia that hosted the ftp site resulted in RF field intensities much closer to the theoretical value expected on the basis of the TPO of the client card in the computer.

A fifth factor is that transmission protocols used by WLANs require bidirectional transmission of data even when the user is receiving or sending files, which reduces the duty cycle of transmission of the AP or client card. Thus, a client that is transmitting a large file to an AP will spend much of its time waiting for error checking from the AP; while receiving data it will also transmit signals. This further limits the fraction of time that the transmitter will be active.

All of these factors conspire to keep the duty cycle of transmission of a client card or AP low. A device can be made to transmit at a high duty cycle for times that correspond to the averaging times of IEEE or ICNIRP limits only under exceptional conditions, for example:

- A very large file must be sent from the device in question;
- No other active users are competing for attention of the network;
- No other WLANs are present that utilize the same channel;
- A transmission protocol is being used that minimizes or avoids the error checking that is normally done by usual protocols; and
- If the data are being sent to a hardwired network, the network must have sufficient capacity to absorb the data being sent to it without slowing down the communication between the AP and client card.

In ordinary use, WLANs can handle ordinary user activities, such as reading email or surfing the Internet, with only a tiny increase in duty cycle of transmission from either the AP or client card beyond a baseline value determined by management functions of the WLAN. To approach a duty cycle of 100% for 6 or 30 min (the averaging time specified in IEEE or ICNIRP exposure limits) would be truly exceptional. And even if the AP or client card were transmitting with a high duty cycle, its output would be comparable to that of a mobile telephone in use. Apart from its reassuring implications for individuals who might be concerned about possible health effects of RF energy, the considerations above have important practical implication in terms of verifying the compliance of APs and client cards with regulatory exposure limits. At least in Europe, APs and client cards are subject to the same compliance testing as mobile phone handsets. In real-world situations, these devices virtually never transmit with full duty cycle, and their time-averaged power output (which is relevant to determining compliance with exposure limits) is invariably far lower than the peak output power. Whether extensive (and expensive) SAR testing should be required for these devices is, at the least, a debatable question.

■ ■