Directional Reconfigurable Antennas on Laptop Computers: Simulation, Measurement and Evaluation of Candidate Integration Positions

Greg H. Huff, *Student Member, IEEE*, Judy Feng, Shenghui Zhang, *Student Member, IEEE*, Garvin Cung, and Jennifer T. Bernhard, *Senior Member, IEEE*

***Abstract*—This study reports on the integration of a novel reconfigurable microstrip antenna capable of reconfiguring both its radiation pattern and frequency response onto a generic laptop computer structure. The purpose of such an exercise is to provide the relevant information necessary to integrate high performance antennas onto structures that can be used in *ad hoc* communication scenarios as well as other demanding applications. To pre-evaluate candidate antenna locations on the laptop chassis, an electromagnetic visibility study (EVS) is performed. Once integrated into candidate positions that have been analyzed by the EVS, the operation of the antenna on the host structure is measured and assessed with consideration to several realistic electromagnetic environments. The resulting performance and packaging issues are discussed. A formalized procedure for the integration of the antenna onto any host chassis using the EVS as a tool is also included.**

***Index Terms*—Antenna integration, antenna packaging, reconfigurable antenna.**

I. Introduction

FUTURE generations of portable communication devices will require high quality wireless links capable of high data rate delivery, as well as the ability to maintain these links in harsh conditions or when communicating with multiple targets. To accomplish this, the use of innovative reconfigurable antenna designs should be considered to sustain the highest quality path for data. When the candidate antenna utilizes both reconfigurable radiation characteristics as well as frequency agility, the performance issues surrounding the integration, packaging and electromagnetic environment of the antenna become increasingly important factors.

Previous integration and packaging schemes have placed radiating elements onto a number of different surfaces and locations on the laptop chassis. The first of these is antenna integration into computer cards [1], [2], which has been investigated and implemented in commercial products, including the implementation of complete RF systems to support the antenna. The next approach is the vertically oriented antenna surface (VOAS) [3], in which a surface is hinged from the top of the screen and swings to keep vertically oriented and more visible to incoming data. Moving closer to direct integration of an antenna, the placement of a novel dual frequency antenna onto a laptop chassis has also been experimentally investigated in [4] as well as an iterative/parametric method of moments investigation of position in [5], which simulates pseudo-integration in different positions. However, aside from the microstrip patch antenna discussed in [5], all of these integration schemes are nonconformal. This condition not only gives rise to electromagnetic constraints, but also serious practical issues as well (including wear and breakage). To avoid some of these issues, an inverted-F antenna has been conformally mounted on a laptop computer prototype in [6] using a primarily experimental methodology to achieve the integration position. Although the outcome is effective and provides meaningful measured results, [6] does not present a conformal integration process that can determine the best location for the antenna. Certainly, a full modal current evaluation of a host chassis and antenna could be considered, each in a unique operating scenario. To avoid these potential pitfalls, the present work develops a process that can expediently predict the conditions for which an antenna capable of altering its radiation and/or frequency characteristics can maintain a maximum degree of reconfigurability once integrated onto a host device.

To investigate the integration of the reconfigurable antenna onto a laptop computer, the following topics are addressed. First, the operation of the reconfigurable antenna is discussed. Next, the electromagnetic visibility study (EVS) is performed on the host chassis, and the pertinent information describing the candidate positions for integration is calculated. With this information, the experimental portion of this study is conducted. The reconfigurable antenna is conformally mounted onto a physical model of a laptop computer, and the VSWR, input impedance, and radiation characteristics are measured for all positions under consideration. While in these positions, the effects of realistic electromagnetic environments are also observed. Finally, with the information obtained from both the EVS and measurements, the candidate positions are evaluated on the merits of reconfigurability and performance.

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G. H. Huff, S. Zhang, C. Cung, and J. T. Bernhard are with the Electromagnetics Laboratory, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA (e-mail: jbernhar@uiuc.edu).

J. Feng was with the Electromagnetics Laboratory, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA. She is now with BAE Systems, Information and Electronic Warfare Systems, Merrimack, NH 03054 USA.

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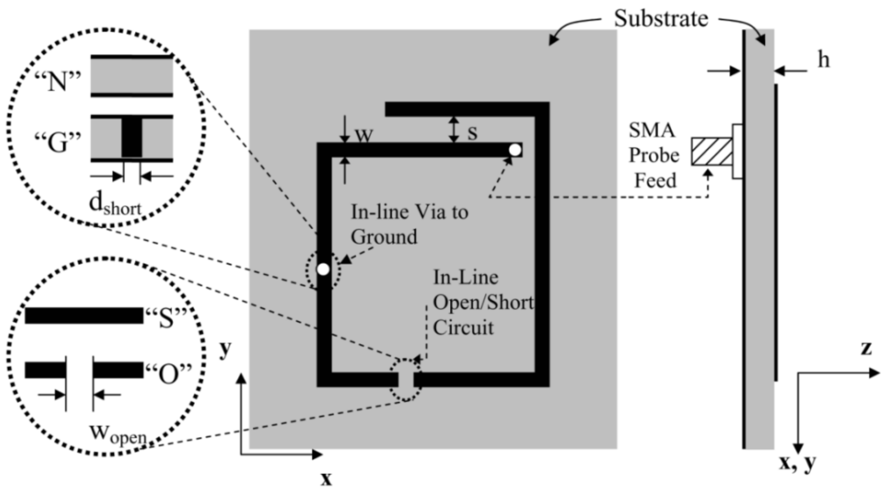

Fig. 1. Antenna geometry, including ground plane and substrate, with tuning elements [7].

II. Reconfigurable Antenna Design

The reconfigurable antenna used in this study is a single turn microstrip square spiral, previously reported on in [7]. The antenna geometry and position of switching elements (hard-wired for proof-of-concept) is shown in Fig. 1. The total length of the spiral is 80 mm, and is determined by approximately one wavelength around the desired base operational frequency. The spacing between the first and last linear spiral sections is 1.0 mm, and the antenna is centered on a grounded Duroid 5880[1] ($\varepsilon_r = 2.2$) substrate with dimensions of 34 mm $\times$ 36 mm. The first configuration of the antenna is that of the base geometry where no tuning elements are added. Hence, moving counterclockwise from the top left corner, the first tuning element is N (not grounded), and the second tuning element is S (an in-line short), creating the NS configuration (the unperturbed single turn square spiral). In all configurations, the E plane is designated as the xz plane and the H plane as the yz plane. The two configurations, reconfigured radiation and reconfigured frequency, are described in the following sections.

A. Pattern Reconfigurability

In the original antenna configuration NS with no tuning elements activated, the length of the square spiral is approximately one wavelength and gives broadside linear polarization along the diagonal in the S band (3.7 GHz). To reconfigure the pattern, two tuning elements are required. The first tuning element is a short to ground G that has a shorting pin diameter $d_{\rm short}$, equal to 1.23 mm and located approximately one-quarter wavelength from the feed position. The second element is an open-circuit in the spiral O, that has a spacing width $w_{\rm open}$ of 1.0 mm. With the shorting pin and the in-line open present (the GO configuration), the antenna behaves more as a shorted quarter-wavelength resonator with a parasitic element (the remaining section of spiral) that helps to maintain the impedance match and create a 45° tilted radiation pattern. In this configuration, the antenna is linearly polarized along the yz plane, with operation at 3.7 GHz, yielding 50 MHz of shared 2:1 VSWR bandwidth between the NS and GO configurations.

[1]Duroid 5880 is a registered product of the Advanced Circuit Materials Division, Rogers Corporation, 100 S. Roosevelt Ave, Chandler, AZ 85226 USA.

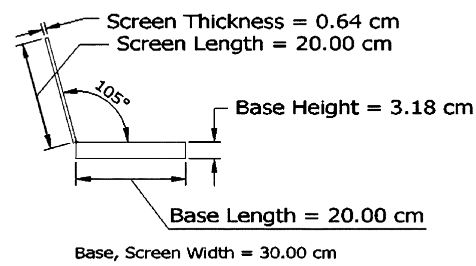

Fig. 2. Laptop computer model (including dimensions) used in EVS simulations and fabricated for experimental portion of position and electromagnetic environment.

B. Frequency Reconfigurability

To change the operating frequency of the antenna, only the in-line open-circuit is activated, giving the NO configuration. In this configuration, the antenna acts as an open-circuited single-wavelength resonator, resulting in a shift in the operating frequency band from S (3.7 GHz) to C band (6.0 GHz). At this higher frequency, the coupling to the parasitic arm formed by the in-line open is reduced. For the reconfigured frequency mode, the antenna is linearly polarized with broadside radiation patterns polarized along the xz plane.

III. Laptop Model

To perform the study of integration and packaging, a generic model of a laptop computer is developed for FDTD simulation and fabricated for experimental verification. The overall dimensions of the generic laptop are: base unit ($20 \times 30 \times 3.18$ cm^3) and screen ($20 \times 30 \times 0.64$ cm^3). The open angle of the computer to simulate actual operation is 105°, and the side profile dimensions of the generic laptop model can be seen in Fig. 2. The fabricated model consists of a Lucite[2] ($\varepsilon_r \approx 3.6$) body, clad in copper tape across the structure (tacked with solder to ensure

[2]Lucite is a registered trademark of Lucite International Ltd., Queens Gate Queens Terrace, Southampton SO14 3BP, U.K.

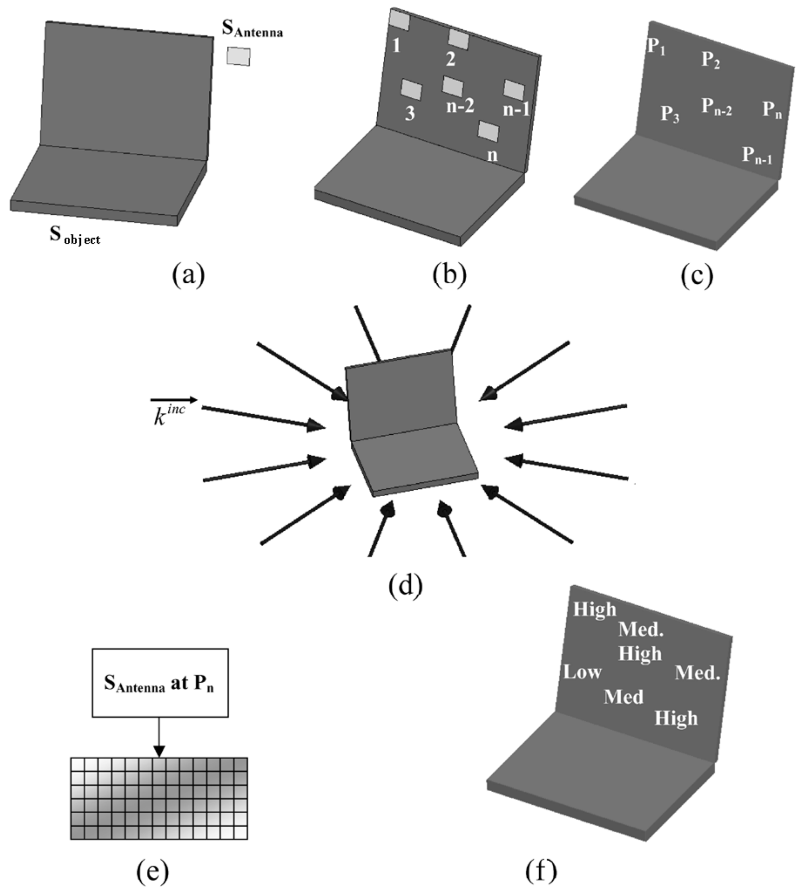

Fig. 3. EVS Study. (a) Laptop surface and antenna surface, (b) realizable positions of antenna on laptop, (c) point representation of integrated position for book keeping, (d) representation of plane waves illuminating the object, (e) representation of surface currents on the laptop surface confined by the antenna's surface, and (f) ranking of position based on evaluation of EVS study.

electrical continuity), which is meant to mimic the computer's internal shielding. Future models may incorporate more materials as well as a variety of different geometries with realistic holes for devices, connectors, etc.

IV. Electromagnetic Visibility Study

For different positions on the laptop chassis, the effects of edge diffraction from surface waves propagating to the neighboring edges and corners of the structure should be considered. However, in most cases these effects will not completely dictate the performance of the antenna once mounted so they have been left for future analysis of higher order effects. To better understand the base relationship between antenna performance and position, an EVS is considered as a first step for integration. The EVS, which can be seen as a shortcut to a full modal and diffraction analysis of the device, was first considered in [8] to aid in the integration process of antennas onto laptop computers. The motivation for the EVS is straightforward, and relies on the fundamental relationship between the induced surface currents on the host device generated from incoming electromagnetic fields and their impact on the antenna's performance. The study works by locating suitable regions on the host chassis with the highest steady-state current, and translates them into regions of visibility, from high to low, for the antenna. The process begins with the host surface (the laptop computer) defined by S_{Object} ($S_{\text{Object}} = S_{\text{Laptop}}$ for this study) and that of the antenna defined by S_{Antenna} [Fig. 3(a)]. A set of guidelines is then followed for the conformal integration scheme.

I. For conformal integration, the antenna surface, S_{Antenna}, must satisfy the physical restraints for placement, and conformally occupy a surface on S_{Laptop} [Fig. 3(b)]:

$$S_{\text{Antenna}} \in S_{\text{Laptop}}. \tag{1}$$

II. Regions satisfying Guideline I create a set of N candidate locations P [Fig. 3(c)]

$$\{P_n\}_{n=1}^{N} = \{P_1, P_2, \ldots, P_N\}. \tag{2}$$

III. The laptop is discritized and illuminated by plane waves incident from all angles in the direction(s), and/or orientation(s), most likely to receive/transmit data. For this study, the plane of incoming data is considered to be in the azimuthal plane of the laptop computer [Fig. 3(d)] in the direction $\overrightarrow{k^{\text{inc}}}$. The laptop is illuminated by plane waves propagating in the azimuthal plane ($\theta = \pi/2$) at intervals of $\Delta\phi$ ($=\pi/6$ for this study), for $0 \leq \phi \leq 2\pi$. This produces a total of M plane waves (where $M = (2\pi/\Delta\phi)$, and

TABLE I
RESULTS FROM THE EVS

	POSITION 1	POSITION 2	POSITION 3	POSITION 4
$\bar{J}_C$ [A/m^2]	0.631	0.522	0.655	0.497
σ [A/m^2]	0.254	0.407	0.291	0.335
EVS Ranking	Medium High	Medium Low	High	Low

$m = 1, 2, \ldots, M$ in (3) below), for which the electric field polarization for these directions can be given as

$$\left\{\vec{E}_m^{\mathrm{Inc}}\right\}_1^M = \sum_{m=1}^{M} \Big(([\cos(m\Delta\phi)\hat{x} + \sin(m\Delta\phi)\hat{y}]_{\mathrm{Horizontal}} + [\hat{z}]_{\mathrm{Vertical}})e^{j(\omega t - k(x\cos(m\Delta\phi) + y\sin(m\Delta\phi)))}\Big). \quad (3)$$

IV. The magnitude of steady state conduction current density $\{|J_m^{\mathrm{Con}}|\}_1^M$ on S_{Laptop} generated by $\{\vec{E}_m^{\mathrm{Inc}}\}_1^M$ can then be determined. Once $\{|J_m^{\mathrm{Con}}|\}_1^M$ is known for $0 \le \phi \le 2\pi, S_{\mathrm{Antenna}}$ is revisited on the set of possible locations $\{P_n\}_{n=1}^N$ residing on S_{Laptop}. In the FDTD solution space, this is realized as the surface of the laptop with discritized spatial dimensions $(\Delta x, \Delta y, \Delta z)$ confined by S_{Antenna} [Fig. 3(e)]. For this study in particular, XFDTD[3] [9] is used to perform simulations, and $\Delta x = \Delta y = \Delta z \approx 0.025\lambda_0$ at 3.7 GHz.

V. With the information generated in Guideline IV, the conduction current density in the region(s) confined by S_{Antenna}, u, (with U being the total number of cells $\{u\}_1^U \in S_{\mathrm{Antenna}}$), can then be used to find the average conduction current density, $\bar{J}_C$, over all incoming angles, M, and its standard deviation, σ

$$\bar{J}_C = \frac{1}{MU}\sum_{j=1}^{M}\sum_{i=1}^{U}\left|J_{ij}^{\mathrm{Con}}\right| \ [\mathrm{A/m^2}] \quad (4)$$

$$\sigma = \sqrt{\frac{\sum_{j=1}^{M}\left(\left(\frac{1}{U}\sum_{i=1}^{U}\left|J_{ij}^{\mathrm{Con}}\right|\right) - \bar{J}_C\right)^2}{M}} \ [\mathrm{A/m^2}]. \quad (5)$$

VI. Using (4) and (5), the areas of interest $\{P_n\}_{n=1}^N$ can be evaluated and ranked using the average steady state conduction current densities as well as the standard deviation within the areas confined by S_{Antenna}.

For the generic laptop computer model used in this study, the candidate positions P can be seen in Fig. 4 and the results from the EVS for these positions presented in Table I. For this example, a set of four candidate locations provides a sample of nonoverlapping positions for comparison. Table I contains the rankings of the four candidate locations from high to low visibility based on their respective local current densities and standard deviations. We hypothesize that positions with higher levels of electromagnetic visibility (higher values of $\bar{J}_C$ and lower values of σ) will support antenna operation closer to that of free space.

[3]XFDTD is a registered product of Remcom, 315 South Allen Street, Suite 222, State College, PA 16801 USA.

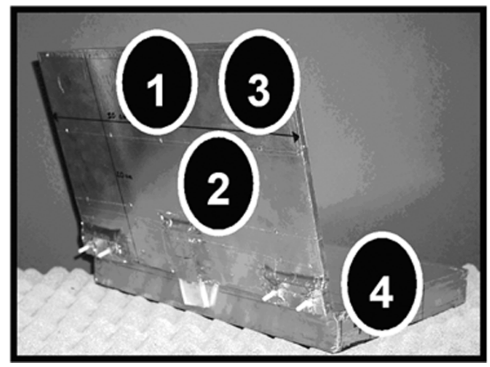

Fig. 4. Fabricated model of laptop computer's internal shielding, showing candidate positions, P_n, (for n = 1, 2, 3, and 4) for antenna integration.

V. ELECTROMAGNETIC ENVIRONMENT STUDY

In order to fully evaluate the candidate positions for antenna integration, it is important to take into consideration both the integration parameters around which the antenna will operate with maximum performance, as well as the conditions that arise from operation in harsh, unfavorable, or changing electromagnetic environments. To investigate the environmental effects on the antenna as it assumes different positions on the laptop, several test environments were created to mimic different working situations. They include: 1) a dielectric surface [Lucite $(\varepsilon_r \approx 3.6)$]; 2) a conductive surface; 3) a dielectric surface with scattering objects; and 4) a conductive surface with scattering objects. These conditions are chosen to represent four basic environmental conditions likely to be encountered by the laptop computer. The scattering objects are an assortment of items placed in the plane of the laptop (stacks of CDs, beverage containers, etc.) that serves as one example of possible "real world" environments.

VI. EXPERIMENTAL RESULTS

To experimentally verify the results from the EVS, the antenna was conformally mounted onto the laptop chassis such that the H plane, or yz plane of the antenna, was aligned with the azimuthal plane of the laptop chassis base unit. With the laptop sitting in the horizontal plane, the radiation characteristics from 1) the NS configuration have linear polarization along the diagonal; 2) the GO configuration is horizontally polarized; and 3) the NO configurations are vertically polarized. For all positions and antenna configurations, input impedance, 2:1 VSWR bandwidth, and radiation patterns were measured. The experimental setup used for this study, including the relative antenna coordinate system on the laptop and the desired free-space radiation of the reconfigured antenna configurations in their primary polarizations, is shown in Fig. 5. To provide

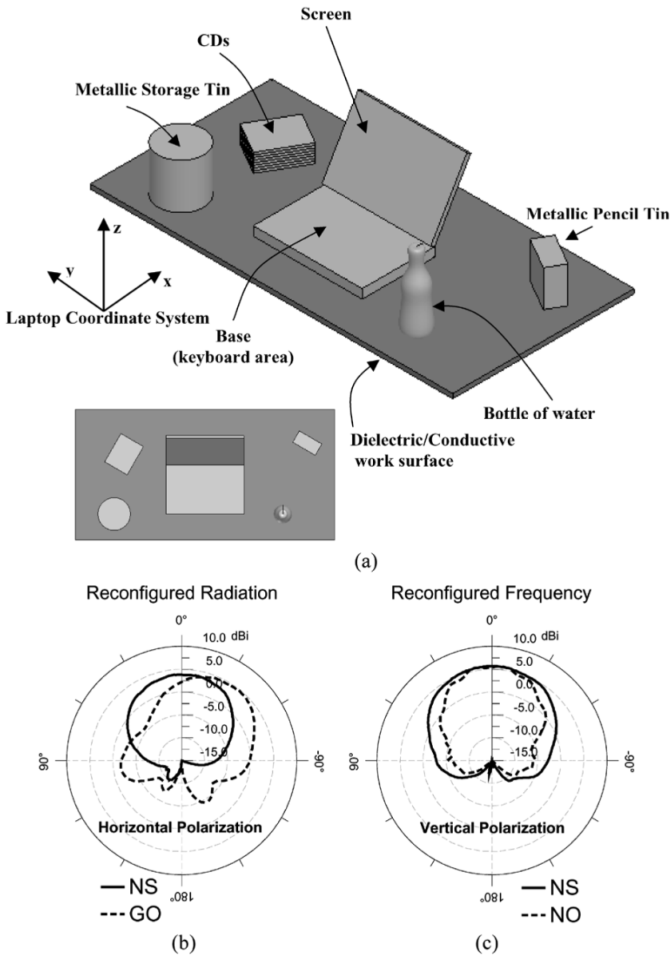

Fig. 5. (a) Measurement setup including scattering objects (not to scale, actual positions differ slightly). (b) and (c) Measured free space radiation patterns of the antenna in the plane of interest for the principle polarization of the reconfigured radiation and reconfigured frequency configurations, respectively.

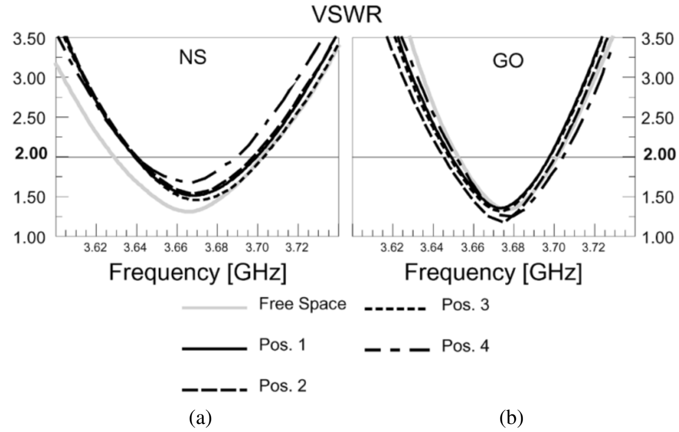

Fig. 6. Measured VSWR of antenna in free space and integrated on laptop for the reconfigured radiation configurations (a) NS and (b) GO.

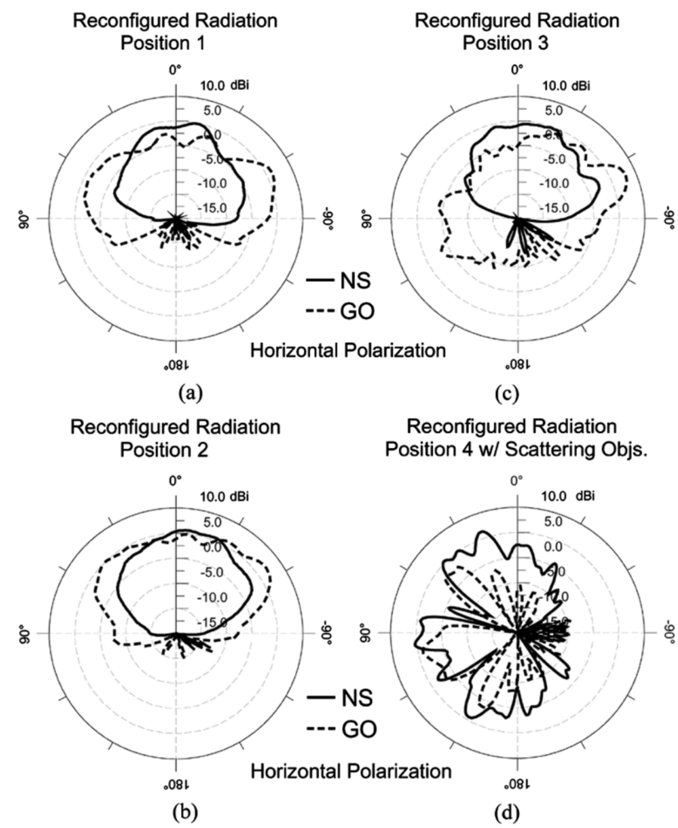

Fig. 7. Measured azimuthal radiation patterns for reconfigured radiation configurations NS and GO with horizontal polarization. (a), (b), and (c) Measurements taken on the dielectric work surface with no scattering objects at positions 1, 2, and 3, respectively. (d) Measurement on the dielectric work surface with the addition of scattering objects for position 4.

a comprehensive comparison of integration position, measurements in the azimuthal plane of laptop have been provided in the following sections. Elevation measurements of the laptop were also performed, but only in the environments without scattering objects and are not shown here since the EVS was performed using incoming waves at azimuth relative to the laptop computer. Elevation measurements do indicate the same general kinds of chassis effects illustrated in the azimuthal measurements.

A. Performance of Reconfigured Radiation Configurations

1) Shared Bandwidth: For the reconfigured radiation configurations the effects of placement on the antenna's performance in terms of the shared bandwidth are addressed first. Fig. 6 shows the VSWR of reconfigured radiation configurations, NS and GO (horizontally polarized with respect to the laptop). For the free space and integrated antenna positions 1, 2, 3, and 4, the shared 2:1 VSWR bandwidths between the NS (base) and GO (reconfigured radiation) configurations are: 50, 50, 54, 50, and 38 MHz, respectively. Although the bandwidths of the antenna are somewhat shifted, positions 1 and 3 show no appreciable loss in shared bandwidth. In position 2 there is a shared bandwidth increase of 4 MHz, and in position 4 there is a loss of 12 MHz in shared bandwidth, indicating that the antenna may not be able to support the currents needed for the desired reconfigurability in those positions. The 2:1 VSWR bandwidths for these configurations demonstrate that the antenna is affected as the integration position changes, and appears to be affected more in positions with low electromagnetic visibility.

2) Radiation Characteristics: The effects of integration position on radiation characteristics are examined next for the reconfigured radiation modes. Fig. 7 contains the azimuthal radiation patterns for the antenna with reconfigured radiation in all positions. As predicted by the EVS, positions 1 and 3 provide the antenna with the necessary conditions to effectively reconfigure the radiation pattern. In position 1, the reconfigured radiation pattern is different from that of the antenna measured in free space; the pattern symmetry can be attributed to the symmetric placement of the antenna with respect to the screen and the behavior of the antenna on a large, symmetric ground plane. Measurements with the antenna in position 3 yield almost identical results to the free-space reconfigured radiation. At position 3, the near free-space operation is attributed to the asymmetric position of the antenna as well as the asymmetric antenna radiation characteristic. However, radiation in this position is scalloped slightly due to edge diffraction occurring at the corner of the screen area (see Fig. 6). This supports the findings of the EVS that indicate a higher standard deviation of currents on this portion of the chassis.

In position 2, the desired reconfigurability is not observed, and the pattern is only reconfigured to a broader beam. Although the desired reconfigurability is not observed at this location, the effects of symmetry from the integration position (with respect to the screen) are evident in the symmetry of the resulting main beam, similar to effects observed at position 1. At position 4, the beam is not successfully reconfigured, and to a lesser degree resembles operation at position 2. These results demonstrate the importance of surface currents to the reconfigured radiation characteristics of this particular antenna.

3) Electromagnetic Environments and Scattering Objects: In general, the effects of scattering objects and electromagnetic environments on the overall operation of the reconfigured radiation configurations are minor at positions 1, 2, and 3 (not shown here for brevity). This is due to the antenna positions on the laptop, which are slightly elevated above the table. However, at position 4 the effects from the scattering objects and electromagnetic environments severely deteriorate the performance of the antenna. At this position, the electromagnetic environment and scattering objects can directly influence or alter the radiation characteristics (in both the NS and GO configuration), such that the pattern characteristics are rendered undesirable. Intuitively, position 4 is not a desirable location for an antenna. In this position the antenna resides in the plane most likely to encounter scattering from random objects placed in the vicinity of the laptop, and also presents the possibility of the radiating element interacting with the work surface. This is demonstrated when the structure resides on the conductive surface and the antenna is integrated at position 4. At this position the antenna experiences a massive reduction in gain ($\sim$20 dB) in the GO configuration (which employs a grounding via) from grounding through the chassis and coupling to the conductive surface. This effect is not shown specifically in Fig. 7 (the decrease in pattern magnitude is too large to meaningfully plot within the range of the other antenna patterns) and is largely an antenna specific issue. However, this measurement emphasizes that position 4 is least desirable for this mode of operation. For a different view of this, Fig. 8(a) and (b) illustrate the effects of the scattering objects on the reconfigurable radiation configurations at position 4 and compare the measured patterns for the antenna and the antenna in the presence of scattering objects on the dielectric work surface.

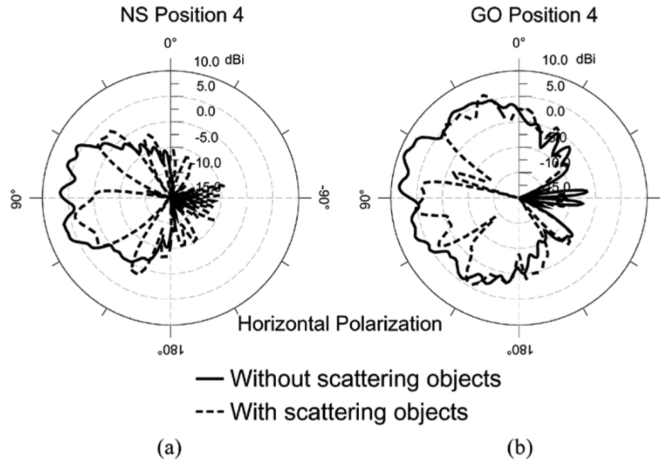

Fig. 8. Measured azimuthal radiation patterns showing the effects of scattering objects at position 4 with horizontal polarization. (a) and (b) Represent the reconfigured radiation configurations NS and GO, respectively.

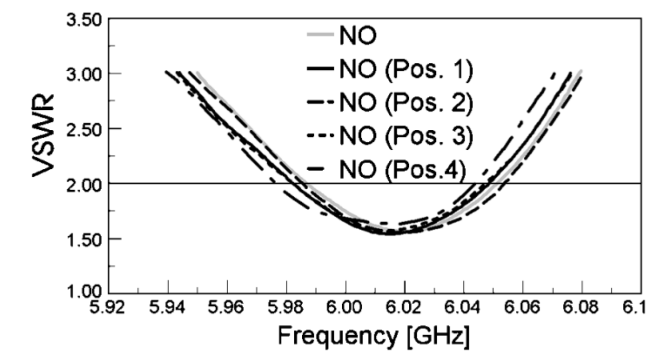

Fig. 9. Measured VSWR of antenna in free space and integrated on laptop for the reconfigured frequency configuration NO.

These plots show that scattering objects in the vicinity of the laptop can influence greatly the antenna's performance.

B. Performance of Reconfigured Frequency Configurations

1) Bandwidth and Radiation Characteristics: For the reconfigured frequency configurations on the dielectric work surface, NS and NO (vertically polarized), local placement of the antenna does not significantly shift or deteriorate the resulting 2:1 VSWR bandwidth (Fig. 9). Fig. 10 contains the radiation patterns for the antenna with reconfigured frequency in all positions. At positions 1 and 2, the antenna experiences a slight increase in gain at broadside but retains desirable pattern characteristics. This characteristic is also seen in position 3, but without a significant change in gain. Operation with the antenna in position 4 appears to be acceptable.

2) Electromagnetic Environments and Scattering Objects: For the first three positions, the location of the antenna prevents significant interaction with the scattering objects, as was the case for the reconfigured radiation mode. Position 4 again shows problematic behavior. In this configuration, the pinching of the beam between two scattering objects (a large metal tin and a stack of CDs) is present for both the base and reconfigured frequency configuration. Although the position and type of scattering objects were chosen at random, placement of an antenna in the most likely plane of scattering objects

TABLE II
INITIAL PREDICTIONS BY THE EVS, EVALUATION OF SHARED BANDWIDTH STABILITY, ANALYSIS OF PATTERN RECONFIGURABILITY, AND RESULTING FINAL RANKING OF THE DIFFERENT POSITIONS

	POSITION 1	**POSITION 2**	**POSITION 3**	**POSITION 4**
EVS Ranking	Medium High	Medium Low	High	Low
Shared Bandwidth	No Change	Increase	No Change	Decrease
Reconfigured Rad.	Desirable	Undesirable	Desirable	Undesirable
Final Ranking	*High*	Medium Low	*Medium High*	Low

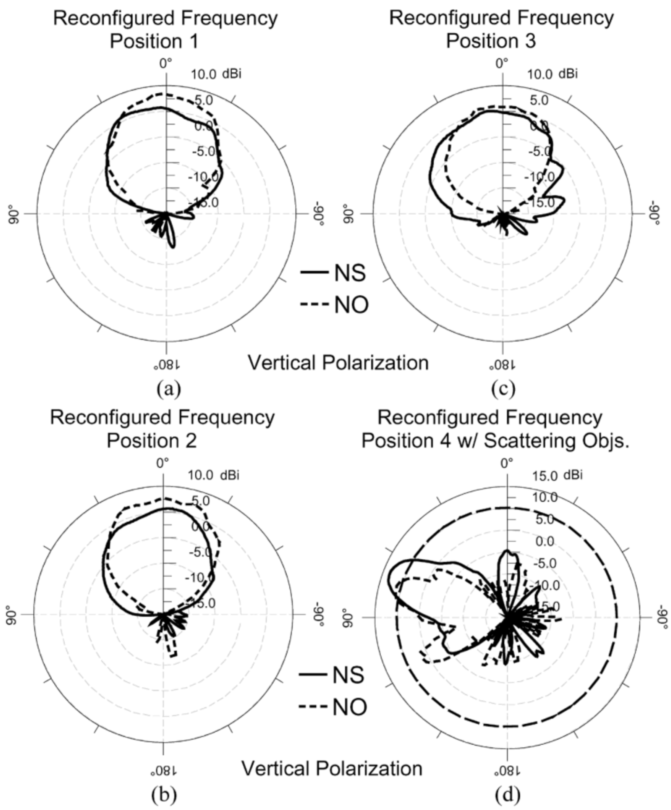

Fig. 10. Measured azimuthal radiation patterns for reconfigured frequency configurations NS and NO with vertical polarization. (a), (b), and (c) Measurements taken on the dielectric work surface with no scattering objects at positions 1, 2, and 3, respectively. (d) Measurement on the dielectric work surface with the addition of scattering objects for position 4 (dashed circumferential line represents plot maximum of all other radiation measurements).

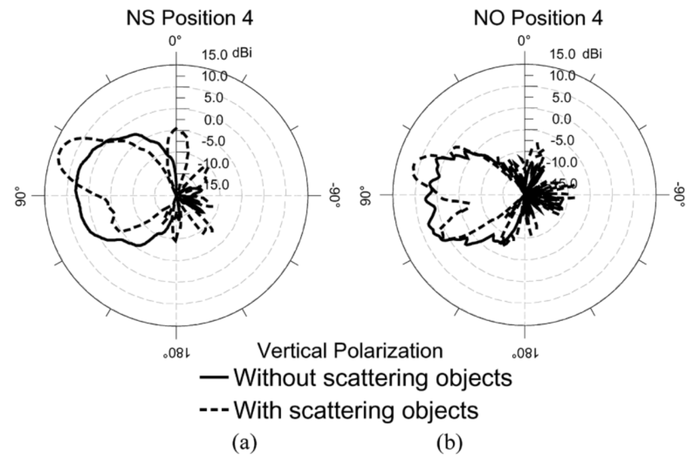

Fig. 11. Measured azimuthal radiation patterns showing the effects of scattering objects at position 4 with vertical polarization. (a) and (b) Represent the reconfigured frequency configurations NS and NO (dashed circumferential line represents plot maximum of all other radiation measurements).

is ultimately undesirable. This is seen in Fig. 11, which illustrates the effects of the scattering objects on the reconfigurable frequency configurations at position 4.

VII. ELECTROMAGNETIC VISIBILITY STUDY REVISITED

For this study, the reconfigured radiation is considered to be the most advantageous objective, and was therefore given a higher priority in the final ranking process than the reconfigured frequency. Results are summarized in Table II. Based on this criterion, position 1 is chosen to have the highest degree of integrated performance, or "highest visibility," on the laptop computer. This differs slightly from the initial ranking of position 3 as most visible with radiation characteristics that mimic free-space operation. While the EVS predicted the best performance of the antenna at position 3, the coverage in the back plane of the screen at position 1 was determined to outweigh the prediction of the EVS alone. For both position 1 and position 3, the reconfigured frequency operated within desirable limits. Position 2 was unchanged from its original ranking, which shows good behavior in the reconfigured frequency but demonstrates no significant pattern reconfigurability other than a slight broadening of the beam. Position 4 also remains unchanged from its original ranking with unacceptable pattern reconfigurability (similar to position 2) and the effects of local scattering objects that can severely deteriorate the performance of the antenna in all modes.

VIII. CONCLUSION

Using the EVS, a conformal antenna integration scheme has been outlined and performed for a novel microstrip antenna capable of reconfiguring its radiation pattern and frequency response. Experimental results of the antenna integrated into different positions on the generic laptop computer chassis, along with a set of changing electromagnetic environments, are encouraging and indicate the feasibility of the process. Although it may be impractical to directly evaluate the performance of the antenna on the laptop, the process (at worst) is able to determine the upper and lower echelons of antenna performance in relation to position with very little computational expense. For this study in particular, the EVS was able to predict the best performance of the antenna at a given position, and its initial ranking was altered only by functionality not considered in the EVS initial analysis. Therefore, techniques such as the EVS, coupled with experimental investigation and verification, can be used to determine the conditions under which a reconfigurable antenna can be successfully integrated onto a host structure.

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[9] XFDTD©, Remcom, Inc., State College, PA, 16801. v5.3.

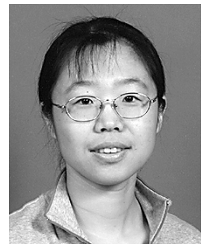
Greg H. Huff (S'03) was born in Oklahoma City, OK, in 1975. He received the B.S. and M.S. degrees from the University of Illinois at Urbana-Champaign, in 2000 and 2003, respectively, where he is currently working toward the Ph.D. degree in the Electromagnetics Laboratory.

His current research involves tunable microwave and millimeter wave devices and reconfigurable antennas as well as electromagnetic compatibility and packaging of high frequency circuits.

Mr. Huff was awarded the 2003 Motorola Center for Communications Graduate Fellowship at the University of Illinois at Urbana-Champaign. He was the co-recipient of the 2004 H. A. Wheeler Applications Prize Paper Award from the IEEE Antenna and Propagation Society.

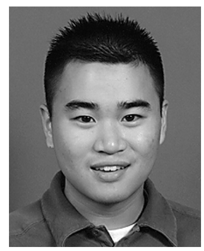
Judy Feng was born in Urbana, IL, on April 12, 1979. She received the B.S. and M.S. degrees in electrical engineering from the University of Illinois at Urbana-Champaign, in 2001 and 2003, respectively.

In September 2003, she joined BAE Systems, Information and Electronic Warfare Systems, Merrimack, NH, where she is currently an Antenna Design Engineer, working on various UHF and VHF antennas for government and military applications. Her current interests include microstrip patch antennas, transistor oscillators, RF systems and microwave circuits.



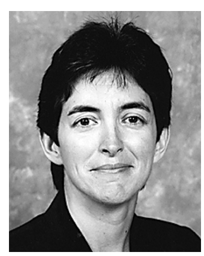
Shenghui Zhang (S'02) received the B.S. degree from the Beijing Institute of Technology, Beijing, China and the M.S. degree in electrical engineering from the China Academy of Space Technology, China, in 1994 and 1997, respectively. She is currently working toward the Ph.D. degree in the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign.

Her current research involves reconfigurable microstrip antennas and electrically small antennas (ESA). Her research interests include millimeter wave and microwave antennas and circuits, reconfigurable antennas, and electromagnetic compatibility.



Garvin Cung received the B.S. degree in electrical engineering from the University of Illinois at Urbana-Champaign, in 2003, where he is currently working toward the M.S. degree.

He is a Research Assistant in the Electromagnetics Laboratory, University of Illinois at Urbana-Champaign. His current interests include wideband antennas and microwave circuits.



Jennifer T. Bernhard (S'89–M'95–SM'01) was born on May 1, 1966, in New Hartford, NY. She received the B.S.E.E. degree from Cornell University, Ithaca, NY, in 1988, and the M.S. and Ph.D. degrees in electrical engineering from Duke University, Durham, NC, in 1990 and 1994, respectively, with support from a National Science Foundation Graduate Fellowship.

While at Cornell, she was a McMullen Dean's Scholar and participated in the Engineering Co-op Program, working at IBM Federal Systems Division, Owego, NY. During the 1994–95, academic year she held the position of Postdoctoral Research Associate with the Departments of Radiation Oncology and Electrical Engineering, Duke University, where she developed RF and microwave circuitry for simultaneous hyperthermia (treatment of cancer with microwaves) and magnetic resonance imaging thermometry. At Duke, she was also an organizing member of the Women in Science and Engineering (WISE) Project, a graduate student-run organization designed to improve the climate for graduate women in engineering and the sciences. From 1995 to 1999, she was an Assistant Professor in the Department of Electrical and Computer Engineering, University of New Hampshire, Durham, where she held the Class of 1944 Professorship. In 1999 and 2000, she was a National Aeronautics and Space Administration-American Society for Engineering Education (NASA-ASEE) Summer Faculty Fellow at the NASA Glenn Research Center, Cleveland, OH. From 1999 to 2003, she was an Assistant Professor in the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign (UIUC), where since 2003, she has held the position of Associate Professor. She is also a UIUC College of Engineering Willett Faculty Scholar and a Research Associate Professor in UIUC's Micro and Nanotechnology Laboratory. Her industrial experience includes work as a Research Engineer with Avnet Development Laboratories and, more recently, as a private Consultant for members of the wireless communication community. She is also a member of the editorial board of *Smart Structures and Systems*. Her research interests include reconfigurable and wideband microwave antennas and circuits, wireless sensors and sensor networks, high speed wireless data communication, electromagnetic compatibility, and electromagnetics for industrial, agricultural, and medical applications.

Prof. Bernhard is a Member of Tau Beta Pi, Eta Kappa Nu, Sigma Xi, and ASEE. She received the NSF CAREER Award in 2000. She and her students received the 2004 H. A. Wheeler Applications Prize Paper Award from the IEEE Antenna and Propagation Society for their paper published in the March 2003 issue of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION. Since 2001, she has served as an Associate Editor for IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION and IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS. She is serving as an Elected Member of the IEEE Antennas and Propagation Society's Administrative Committee from 2004 to 2006.