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Antenna Design Methodology for Smartwatch Applications

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In the early 1990s, Mark Weiser of Xerox predicted that computers would find their way into every part of our daily lives by integrating seamlessly and unobtrusively—a concept he termed ubiquitous computing. "The best user interface," Weiser observed, "is the self-effacing one, the one that you don't even notice." He predicted the advent of a wireless network of connected devices, making information accessible at any time and in any place. According to Weiser,[1] "In the long run, the personal computer and the workstation will become practically obsolete because computing access will be everywhere: in the walls, on your wrist and in 'scrap computers' (like scrap paper) lying about to be used as needed."

The technological world transforms daily into the likeness of Weiser's vision. Smart devices, particularly those that are wearable, like smartwatches, have touched and enhanced all aspects of our lives, from the way we conduct business to the way we relax at the end of the day. The particular advantage of wearable technology comes to the forefront in health and fitness. Wearable devices can monitor heart rate, skin temperature, distance traveled, even food intake and sleep patterns. Currently, most fitness trackers are mounted on wristbands like watches; a few even include watch functions.[2]

The pocket watch was invented in 1762.[3] Although this was a significant revolution, placing the ability to keep time at the fingertips of the common person, instead of the elite, had its disadvantages. If the hands of the user were already full, the manipulation of a pocket watch was just too much hassle —thus, the invention of the wristwatch and its widespread acceptance among British soldiers during World War I.[4] The wristwatch quickly became among the most common wearable devices in the world, making it a prime candidate for enhancement with computer power. Calculator watches first appeared in 1975. They were followed by a wrist PC in the 1980s and a watch with a built-in arcade game.[3] Later smartwatches have only increased their capabilities. 2000 saw what is believed to be the first collaboration between a clothing company and a digital technology company, when Nike and Apple joined to create a fitness tracker embedded in a shoe and designed to work with an iPod. This Nike+ tool was developed to help runners track time, distance, pace and calories burned. Eight years later came the Fitbit Classic. Fitness trackers have flourished, more or less, since.[3] According to mobile communications analysts, the wearables market could be worth $34.2 billion by 2020. Shipments of fitness trackers are expected to reach over 60 million units in the next year or so, while smartwatches are forecast to exceed 30 million units.[3] Computing access is indeed everywhere.

CHIP ANTENNAS

Ubiquitous computing makes good antenna design essential. Smart device antennas must be small and flexible to fit in small, predefined environments. Some research suggests that the bulkiness of smartwatches has tempered their popularity.[5] To be useful, these devices need to operate reliably for a long time without the user needing to modify his or her activity to accommodate the device. This means that the antenna must respond to movement and be immune to the near field effects of the human body. The battery life of the device must also be sufficiently long to satisfy the user. This is largely a function of good antenna design, as most of the energy a smart device uses is consumed during RF transmission. Finally, the completed device must meet user expectations for price and the FCC's requirements for safety.[6]

One solution to these design challenges is the chip antenna. A chip antenna is small and efficient enough to be integrated neatly into a compact smart device, and it is easy to tune.[7] Compared to other options, chip antennas are relatively inexpensive, yet effective. These chips are typically based on helix, meander or patch antenna designs.[8] Because of their cost effectiveness, small size and mechanical viability, analysts forecast the global market for the chip antenna to grow at a 10 percent compound annual growth rate (CAGR) from 2016 to 2020. As more devices trend to wireless connectivity, the boom in smart devices is spurring competition between the various chip vendors, including Vishay Intertechnology, Antenova Ltd., Johanson Technology, Mitsubishi Materials and Fractus.[9]

As with all product developments, designing with chip antennas presents challenges that must be accounted for in the initial circuit design. Recall that we are dealing with small devices. This presents a difficulty because the smaller the antenna, the harder it is to achieve good impedance matching and a large bandwidth.[10] Therefore, performance is highly dependent on the placement and size of the antenna.[7] Second, datasheets reflect the chip on a board, and any variation in the ground plane will change the antenna pattern and impedance. The overall performance of any chip antenna is always dependent on the whole system; it must be compatible with the size and layout of the board, the complexity of the circuit and the type of enclosure.[8] Also, it must not negatively affect any sensors in the device.[7] Finally, on a person, the highly variable dielectric constant of different body tissues causes the blockage and impedance to change.[11] Human tissue is extremely lossy, so electromagnetic energy from an antenna on the body will not propagate through the body and radiate into space as intended, but will largely be absorbed.[10] The results are bulk power absorption, radiation pattern distortion and antenna detuning.[11] Losses can block coverage to other devices or reduce the range of the antenna.

To address these design challenges, a systematic design approach has been developed:

- Choose a chip antenna with a demo board
- Model the chip antenna without the board
- Model the chip antenna with the board
- Measure the chip antenna on the board
- Validate the model with the measured data
- Model the chip antenna in the smart device
- Model the device with a human phantom.

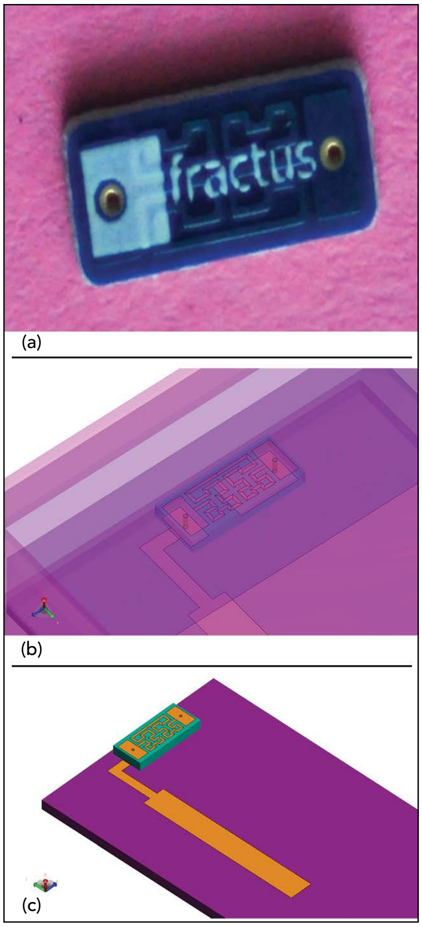
This methodology provides a valid starting point that eliminates a plurality of unknowns. By following the procedure, installation concerns can be addressed with confidence.

For this article, we used a commercially available electromagnetic simulation tool, FEKO[12] and its various full wave solvers, to model the antenna, including the packaging and enclosure of the smart device. The finite element method (FEM) solver is a perfect tool for complex multi-dielectric volumes in close proximity to an antenna. By using the FEM solver, the ground plane can be modified to fit the smart device package and verified to operate properly. Extending the simulation to include a phantom model will show power absorption, radiation pattern distortion and antenna detuning problems that need to be addressed. Given the computational complexity of adding an entire phantom, we used the source decomposition method in FEKO to represent the FEM region of a device as a near field source, then applied the decomposed source to the full phantom model using either the method of moments (MOM) or multi-level fast multipole method (MLFMM).

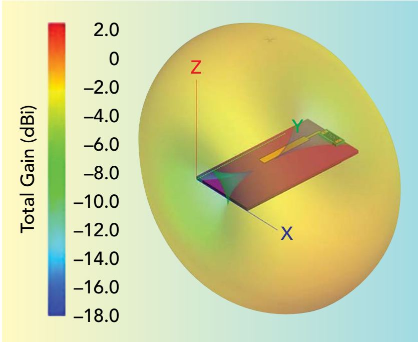
CHIP ANTENNA MODELING

For the smartwatch design, we chose a Fractus Slim Reach Xtend chip antenna (FR05-S1-N-0-104). This chip has been engineered for wireless applications operating in the 2.4 GHz Bluetooth band. The Slim Reach Xtend has the advantages of being small, cost effective and relatively easy to design with, avoiding the need to test multiple antennas with different resonant frequencies.[13] The Slim Reach Xtend datasheet shows the configuration used to determine the performance in the specifications. By integrating the chip antenna with the evaluation board, which can be purchased (EB_FR05-S1-N-0-104), the measured performance can be compared to the modeled simulation, providing a verified model to be used in any smart device design.

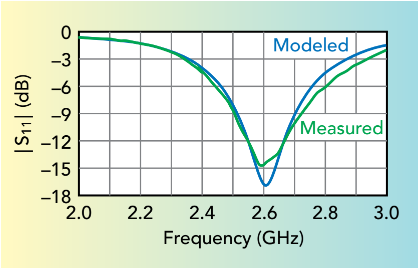
From a close-up of the Fractus chip, the traces on the chip and the geometry of the evaluation board were scaled using a caliper and entered into the FEKO 3D Modeler, CADFEKO. With this information, an FEM model of the Fractus chip on the evaluation board was created. ***Figure 1*** shows a photo of the Fractus chip and the FEM 3D model. The model was run with FEM Solver in FEKO to compute the currents, impedance and antenna patterns. ***Figure 2*** shows the 3D radiation pattern around the chip on the evaluation board. The evaluation board acts like a dipole antenna whose arms lie along the



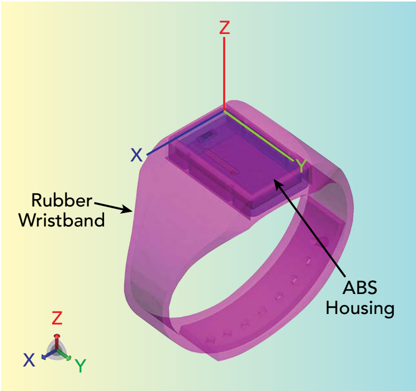
▲ **Fig. 1 Fractus chip antenna photo (a) and FEM model of the chip (b) and evaluation board (c). Courtesy: VStar Systems Inc.[14]**



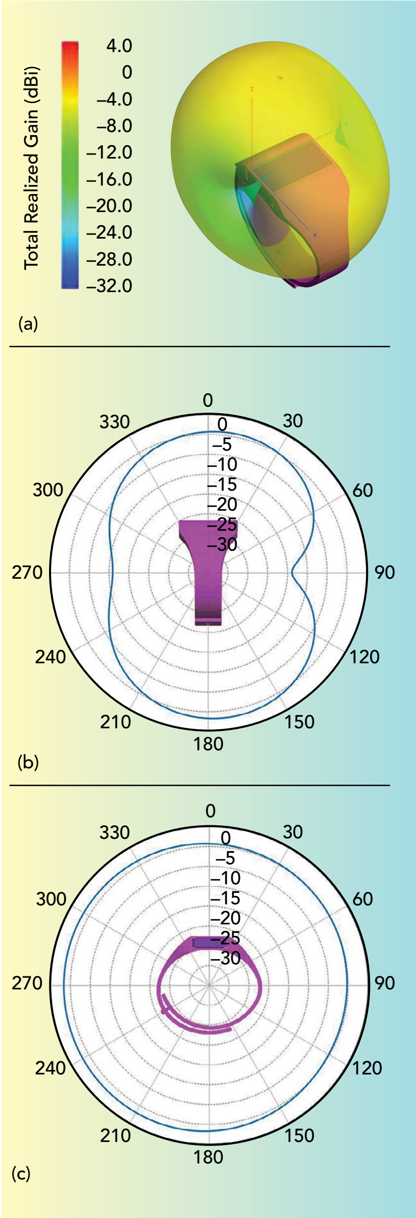
▲ **Fig. 2 Simulated 3D radiation pattern around the Fractus chip antenna evaluation board. Courtesy: VStar Systems Inc.**



▲ **Fig. 3 Measured and simulated $|S_{11}|$ of the Fractus chip antenna evaluation board.**



▲ **Fig. 4 Smartwatch showing the chip and feed network.**



▲ **Fig. 5 Smartwatch simulated 3D antenna pattern (a) and far field antenna gain for φ = 90° (b) and φ = 0° (c) at 2.45 GHz.**

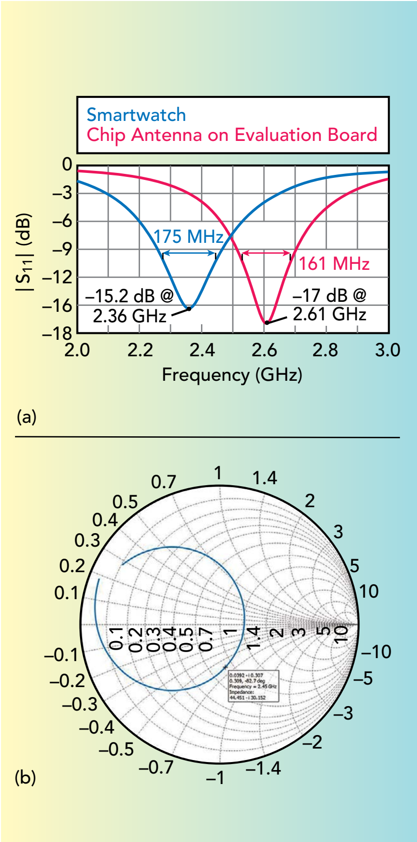
y-axis, accounting for the resulting nulls along that axis.

A comparison of the measured and modeled $|S_{11}|$ of the evaluation board (see ***Figure 3***) shows good agreement for the 10 dB bandwidth, well within acceptable parameters, and the tuned frequency results were nearly identical. This shows excellent correlation between the model and the real board, validating the models of the chip and the chip on the board. This was the first attempt in the modeling and validation process; no other validation steps were required.

SMARTWATCH INTEGRATION

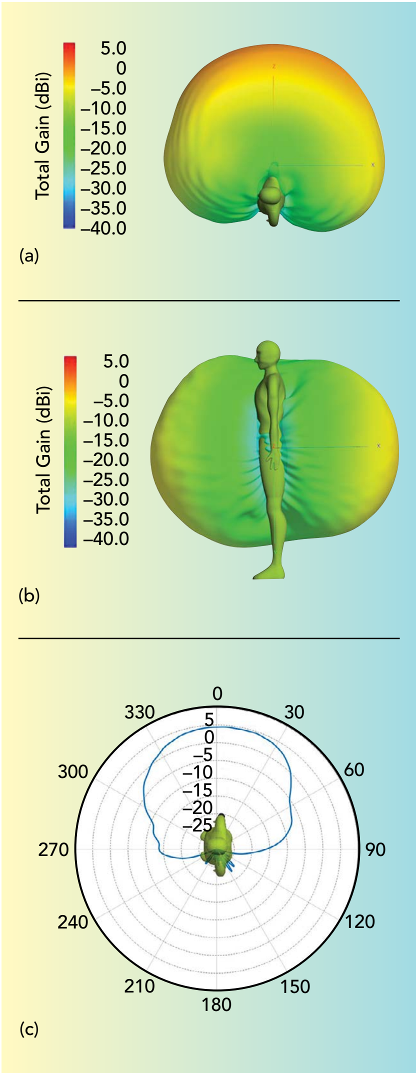
The chip antenna and feed network were integrated into a smartwatch (see ***Figure 4***). As the already complex dielectric geometry of the chip and evaluation board became more complex with the addition of the rubber wristband and ABS plastic electronics housing, the FEKO FEM solver was again selected for simulation. The completed FEM model of the smartwatch geometry was modeled with the solver, calculating the input port impedance, currents and the 3D radiation patterns. ***Figure 5a*** shows the simulated 3D antenna pattern of the chip and PC board embedded in the ABS enclosure and wristband inside the watch. The resulting nulls along the y-axis of the watch maintain the dipole-like pattern along the long axis of the board. The nulls are in the desired position: wearing the watch with the arms down, the nulls in the radiation pattern are directly down to the ground and directly up (the nadir and zenith). Most of the power should be going around the wearer of the watch, and that is what the results show will happen. ***Figure 5b*** shows a φ = 90° cut of the radiation pattern, with the up and down nulls at θ = 90° and θ = 180°. The radiation pattern around the arm is omnidirectional, as shown in ***Figure 5c***.

Integrating the chip antenna into the watch changes the impedance



▲ **Fig. 6 The smartwatch structure "tunes" the antenna, reflected by a change in $|S_{11}|$ (a) and impedance vs. frequency (b).**

(see ***Figure 6a***). The base model has a resonance of 2.6 GHz and a bandwidth of 161 MHz. Embedding the antenna into the surrounding dielectric material reduces the resonant frequency because the dielectric constant of the containing volume is higher. The minimum $|S_{11}|$ drops in frequency since the antenna appears larger. The resonance frequency was reduced from 2.6 to 2.35 GHz, and the bandwidth was increased from 161 to 175 MHz. Note that the resonance frequency drops below the desired Bluetooth band (2.4 to 2.5 GHz). This must be addressed in the final design by adding a matching network to move the response into the Bluetooth band and will not be difficult (see ***Figure 6b***). It is always good practice to place a pi network between the antenna and the transceiver. In this case, a shunt inductance along with a series inductance will tune the antenna to the center of the Bluetooth band while maintaining the bandwidth.



▲ **Fig. 7 Simulated 3D antenna pattern using the full human phantom model, with the smartwatch on the right wrist. Top (a) and side (b) views and far field antenna gain with Θ = 90° (c) at 2.45 GHz.**

HUMAN PHANTOM MODEL

The final step in the design process is to integrate the smartwatch into a full human phantom model to investigate the radiation patterns of the smartwatch in proximity to the human body. Because of the size of the problem, the resources required to run the finite element model of the watch and the human phantom together were prohibitive. Therefore, source decomposition was used to break the problem into two sections: an equivalent source representation of the watch and the equivalent source integrated into the phantom model. Near fields were run around the FEM model of the watch to create an equivalent source to use with the phantom model. Then the MLFMM solver in FEKO was used to solve the phantom. This process greatly reduced the resource and time requirements without compromising accuracy.

Figures 7a and ***b*** show the 3D antenna radiation around the phantom. As expected, the human body is blocking the radiation patterns to the left-hand side, the side opposite the smartwatch. Since the arm is not stationary during normal activity, a connection will normally be maintained between the smartwatch and other transceivers. Excellent radiation patterns are obtained in the front, back and right-hand side of the human body model. ***Figure 7c*** shows the antenna radiation on the horizon around the phantom. The peak gain is just less than 5 dBi, and the overall coverage will meet the requirements for a typical single transceiver design.

CONCLUSION

Designing antennas for wearable smart devices presents a unique set of challenges, i.e., dealing with small environments and lossy human tissue. While the chip antenna offers the efficiency necessary to offset some of these problems, concerns must be addressed during the initial circuit design. Placement, compatibility with the whole system and reliability on a human must be taken into account. To address these, it is beneficial to establish a valid model of the chip antenna that can be integrated into other devices with a high level of confidence. As this article demonstrates, using multiple FEKO solution techniques can solve complex geometric problems with high accuracy. This results in a valid model that can be used to design future applications with high confidence in achieving satisfactory real world results. ■

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