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EXPERIMENTAL STUDY ON THE EFFECTS OF HUMAN AND ELECTRONIC-MECHANICAL INTERACTION ON RF SIGNAL STRENGTH FOR A PERSONAL SERVER

Michael Montero
Berkeley Manufacturing Institute
University of California-Berkeley
montero@kingkong.me.berkeley.edu

Trevor Pering
Intel Corporation
Santa Clara, California
trevor.pering@intel.com

Umair Udaud
Linear Technology Corporation
Milpitas, California
udaud@uclink.berkeley.edu

Paul Wright
Berkeley Manufacturing Institute
University of California-Berkeley
pwright@me.berkeley.edu

Roy Want
Intel Corporation
Santa Clara, California
roy.want@intel.com

ABSTRACT

This paper describes experimental results for transmission quality based on antenna direction, packaging materials, and interactions with the local environment. Many mobile devices depend heavily on wireless communications for their operation, making antenna efficiency very important for their successful operation. The Personal Server (PS) research platform enables the user to carry with them their palm-size personal computer anywhere they go. By simply approaching another computer, a kiosk, or other computing interface, all of the user's data is accessible by wireless connection and transferred to the receiving device. The prototype acts like a mobile server that the consumer can take with and depending on the situation can interact with through any available computing device such as laptops, PCs, tablets, etc. Since the PS uses RF transmission to send files and images to the interfacing computers, maintaining reliable and robust signal strength is important for the device. An experimental approach was used to better understand the factors which may degrade or augment signal strength. The approach taken in this investigation quantifies the effects of human and electronic-mechanical factors on the transmission strength of the PS and help guide decisions on design changes that would favor an improved quality of signal.

The investigation looked at two specific areas that could potentially influence signal performance: i) human interaction and usage ii) electronic-mechanical design factors. The first part of the investigation looked at how the device performed in the presence of a human body, specifically the way it was positioned with respect to the user as well as the position of the human body with respect to the receiving antenna. In addition, the signal strength was observed when the PS was in the presence of other objects commonly carried along the human body. The remaining part of the experiment concerned itself with the given design of the device, specifically the PCB components and plastic casing. Factors from both the electronic and mechanical domains, such as battery placement, paint presence on housing, and geometry of casing, were varied simultaneously using a Design of Experiment (DOE) approach.

KEYWORDS

RF signal experiments, electronic-mechanical design, design of experiments

INTRODUCTION

The development of the PS is motivated by overcoming the limitations of small-screen mobile devices, having available an "always on" mobile solution and leveraging properties of short-range wireless. The PS addresses the issue of ubiquitous computing. Ubiquitous computing is roughly the opposite of virtual reality. Where virtual reality puts people inside a computer-generated world, ubiquitous computing forces the computer to live out here in the world with people. Virtual reality is primarily a horse power problem; ubiquitous computing is a very difficult integration of human factors, computer science, engineering, and social sciences [1].

There exist barriers that ubiquitous computing have always encountered. For instance, mobile computing displays and keyboards are mostly inadequate for performing business or personal tasks where the devices are either too small making them uncomfortable to interact with or too big (heavy laptops, 4 to 6 lbs) making them a mobile nuisance. Another obstacle involves the variability of wireless bandwidth at different locations. In some cases, certain locations may not offer wireless bandwidth or the quality of transmission may be unacceptable for a given application. In addition, network administration may prevent ease of connection given the level of security or types of firewalls in place. Also, costs are associated with the access of wireless bandwidth and scale proportionally as the device to transmitter distance increases (as does the power required for transmission).

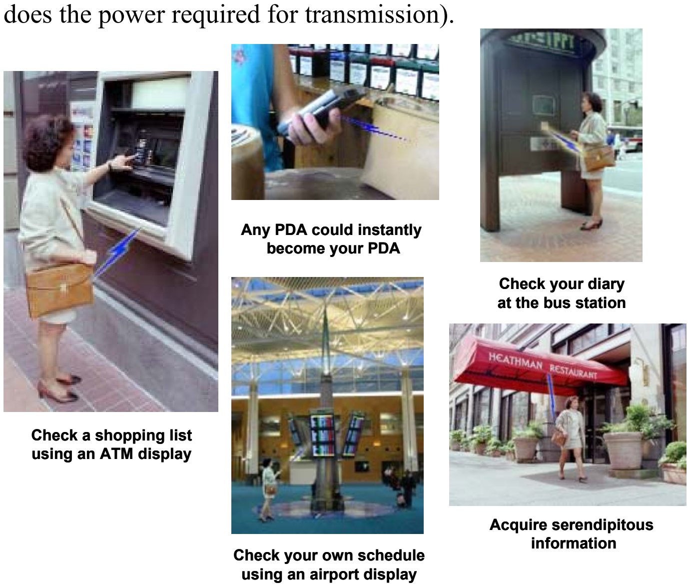

Figure 1. Examples of interface hosts [2].

The PS allows the consumer to carry all their applications and data on them, without the heavy input/output devices. As a results, form factor and mechanical design of the casings plays an important role in regards to usage [3]. Data and information is the essential tool that end users rely on and the physical embodiment may exist as a seamless belt-buckle or watch on one's body. With the PS acting as an unobtrusive personal body server, the device must utilize the local infrastructure to communicate and interact with the server's data. Hence PC displays, keyboards, kiosks, information boards and other mobile devices become the medium by which the PS interacts through. These mediums are called the interface hosts and examples of them are shown in Figure 1.

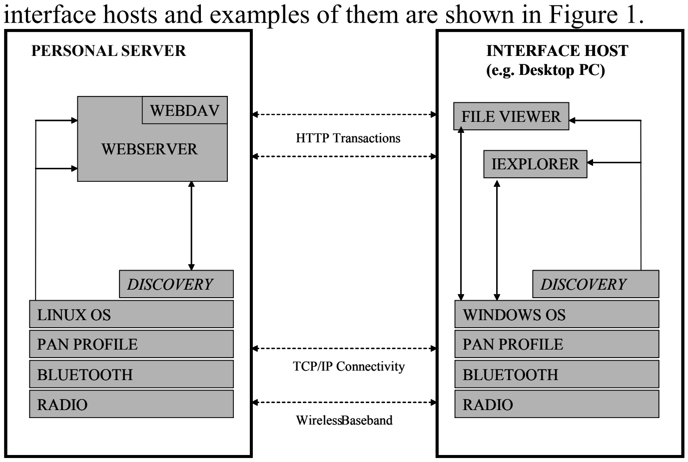

Figure 2. Software structure for both PS and interface host [2]

The basic architecture for the PS and interface host is shown in Figure 2 highlighting the use of standard protocols for the transmission of data. Ease of use is a priority for the design of the device and an important function of the PS is to provide a constant, uninterrupted connection through a short-range wireless network utilizing a Bluetooth processor. Bluetooth processors enable seamless voice and data connections between a wide range of devices through short-range digital two-way radio. Bluetooth essentially provides an open specification for short-range communications of data and voice between both mobile and stationary devices.

ANTENNA SELECTION AND SPECIFICATIONS

The antenna selected for the PS is a surface mounted device or SMD metal strip antenna manufactured by GigaAnt. The antenna was designed for the 2.4 GHz range, specifically to function with the Bluetooth processor. Geometrically it possesses a low profile build height well suited for dense packaging devices such as laptops, mobile phones, PDAs and headset products (see Figure 3).

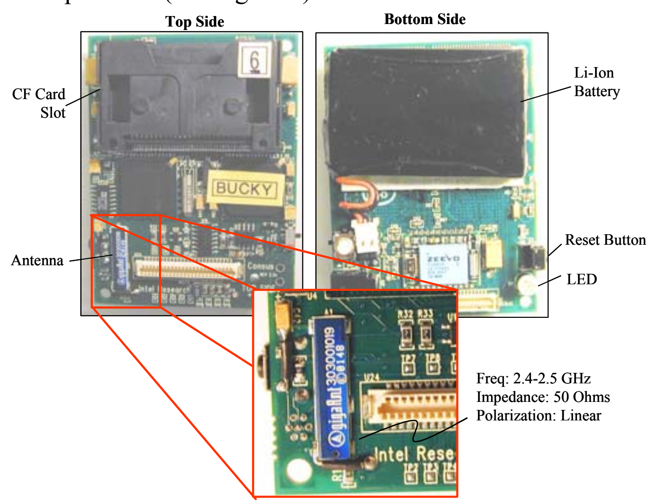

Figure 3. PS system board showing GigaAnt SMD Antenna

With respect to a reference PCB, the antenna ideally radiates in an omni-directional fashion as shown by the three-dimensional radiation pattern provided by GigaAnt in Figure 4. The pattern is generated by measuring the radiation intensity in all three reference planes of an antenna that is placed on a reference PCB that contains no other components. Antenna placement becomes an important factor in attaining a strong and efficient signal. During the development of the PS's system board, the positioning of the antenna became fixed at the time experimental studies where made possible so its location could not be altered.

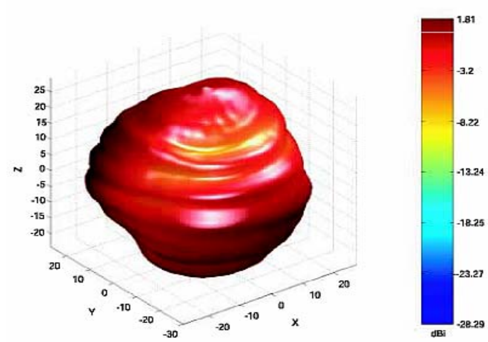

Figure 4. 3D radiation pattern for antenna test using reference PCB [4]

PRELIMINARY STUDY: RADIATION PATTERNS AND SIGNAL DROP-OFF

A standard radiation pattern test was conducted for the PS system board alone to gain a more a realistic picture of the gain distribution for the antenna in the presence of other PCB components. Using an adjustable fixture, free of any metal, that can be oriented in three planes, the device is rotated about a fixed point at increments of 10º for 360º in each plane (XY, XZ and YZ). The fixture is set at a fixed distance of L = 3'7" from the Transverse ElectroMagnetic (TEM) receiving antenna as shown in Figure 5. The TEM receiving antenna allows a more sensitive and highly directional form of reception needed to capture the signal transmissions [5].

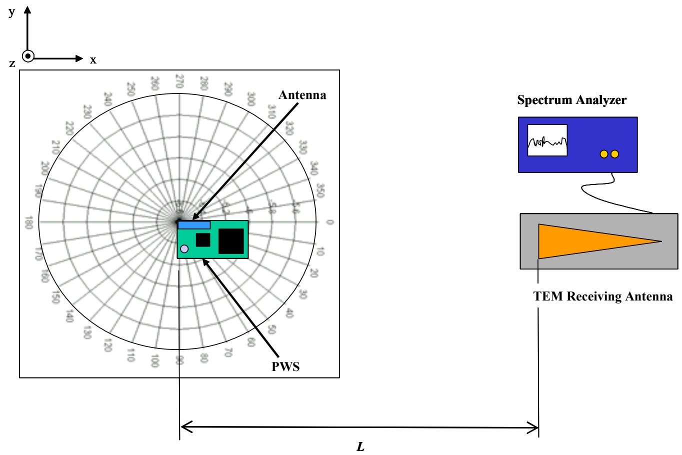

Figure 5. Setup for capturing system radiation pattern

Signal strength was recorded in dBm at one frequency, 2.4080 GHz. Measurements are made after a settling time of approximately 15 seconds per rotation. The testing was conducted in a fairly RF insulated lab of the Berkeley Wireless Research Center (BWRC) in order to minimize interference from other wireless electronics working on the same bandwidth. Given the lack of anechoic chamber, the use of the TEM receiving antenna helped in improving the sensitivity of the measurements. In addition, signal drop-off measurements were recorded with the device held in the YZ plane at the 180º position and incrementally moved away in a straight line from the TEM receiving antenna at 1 ft. increments for approximately 25 ft.

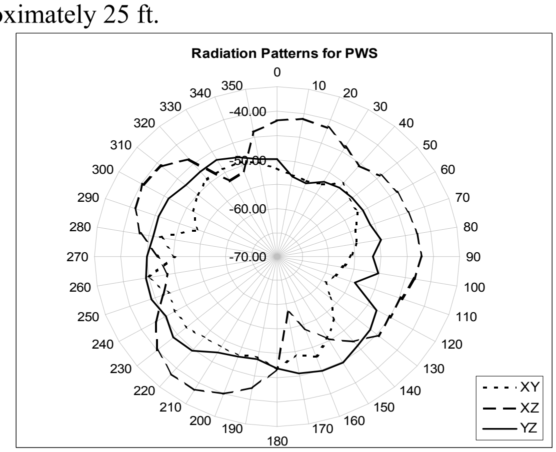

Figure 6. Radiation patterns (dBm) for PS in XY, XZ and YZ planes

Surprisingly, the XZ orientation yielded the stronger signals but had more defined lobes as shown in Figure 6. The YZ has a more consistent circular shape but the signal strength is lower overall than that of the XZ orientation. The XY orientation yielded an even slightly lower strength of signal than the YZ plane but maintained a circular shape more or less. The standard deviation of error varied from plane to plane ranging from 0.25 dBm to 1.50 dBm, which are both approximately within the range of the variation measured from previous studies on an earlier iteration of the PS.

The YZ plane in the 180º position was selected for the signal drop-off measurements based on recommendations by Intel's research developers in regards to the location of the device worn by the consumer. Figure 7 shows the signal strength as the device was incrementally moved back from the receiving antenna. The trend appears to be an exponential decay where the signal strength drops a little more than 20 dBm within the first 7 feet. After which the signal flattens out and becomes difficult to discern from noise, which is approximately around –65 dBm or less.

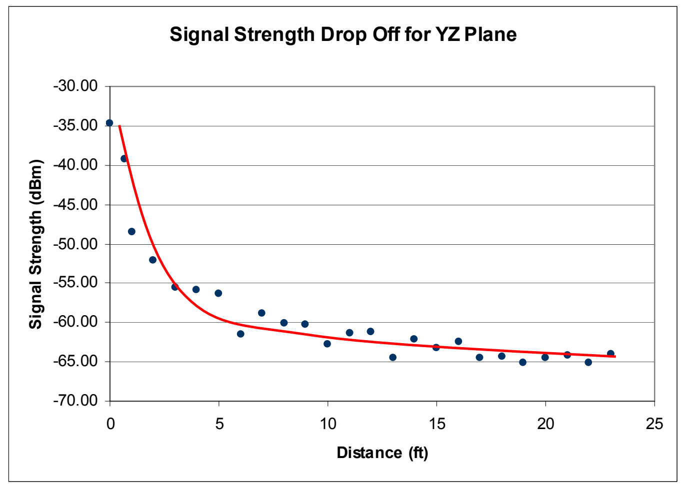

Figure 7. Signal strength drop off plot for YZ plane

Given the antenna orientation, it was expected that the YZ plane would yield the strongest signals but instead the XZ orientation yielded the largest signal strength. The effects of reflected radiation for the increase in the XZ signals was considered after an anomaly was experienced during the drop-off test around 6 feet where the signal strength dropped at 7 feet (see Figure 7). Replications were conducted at both 6 and 7 feet positions to confirm the findings. The drop-off test gives us the ability to explain the drop in intensity due to orientation changes by equating them to values measured at different distances. The drop-off test shows how signal strength decreases as the device moves away from the receiving antenna and hence could drastically impact the quality of signal.

The preliminary study suggests that a more robust orientation would be the YZ plane given the qualitative assessment of the circular distribution of signal strength. The drop-off study suggests that an appropriate distance between the PS and the interfacing host should be within 5 feet. Given these initial guidelines, the selection of orientation and distance were used for the proceeding experiments, DOE 1 and DOE 2.

DOE 1: INVESTIGATION INTO ENVIRONMENTAL AND HUMAN INTERACTION ON RF SIGNAL STRENGTH

A DOE was conducted on the PS device specifically dealing with the antenna and its strength of signal. The goal of the experiment was to gain a better understanding of the effects of signal degradation due to user interaction, user orientation, device location, and the presence of other electronics. The strength of transmission was measured using a spectrum analyzer and a TEM antenna for reception as shown in Figure 8.

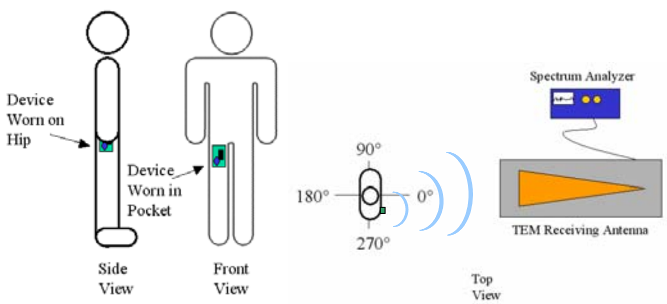

Figure 8. Experimental setup of subject and device for DOE 1

Parameters that were varied are listed in Table 1. Variable A was a four level parameter representing the different body positions or orientations the user was in with respect to the receiving antenna. Body position was at a fixed distance of 3'7". Variable 3 was a two-level parameter representing two different body types, specifically average and above average waist size, in order to see any impact on signal absorption due to body mass.

Factor Code	*Factor Name*	*Levels*			
		0	***1***	***2***	***3***
A	Body Position (Degrees)	0	90	180	270
3	Body Type (Waist Size)	Mike	Paul		
4	Wireless Electronics Present (Cell)	Yes	No		
5	Electronics Present (PDA)	Yes	No		
6	Metal Present (Keys)	Yes	No		
7	Device Location	Hip	Pocket		

Table 1. Definition of factors and factor levels for DOE 1

Variables 4 and 5 are two-level parameters which involved the presence or absence of other electronics (cellphone and PDA) placed in the pocket of the user. Variable 6 simply includes the presence or absence of any other metal such as house keys placed in the pocket. Finally, variable 7 is a two-level parameter indicating the location of the device relative to the user (worn on the hip or in the right front pocket as shown in Figure 8. Variables 4 through 6 are either present or not present in the right front pocket.

The actual design of the experiment is shown in Table 2. The design is a 32-run mixed-level fractional factorial design. Two replicates were recorded at a single frequency while the device remained in hop mode. Figure 9 shows a plot of signal strength (dBm) versus each parameter when set at low or high levels (for body position, the level settings are four-level). Since the decibel values are negative, the less negative the value, the stronger the signal. It's clear to see that as the body position rotated through all 4 positions, the average signal strength decreased. The plot also shows the effects of the rest of the parameters on signal strength. The significance of other electronics present cannot be seen given the large effect of body position.

Test	*Run*	*A*	*3*	*4*	*5*	*6*	*7*	freq1_1	freq1_2
1	1	0	-1	-1	-1	-1	1	-45.67	-46.33
2	2	0	-1	-1	1	1	-1	-59.00	-55.33
3	3	0	-1	1	-1	1	-1	-59.50	-59.83
4	4	0	-1	1	1	-1	1	-53.50	-51.00
5	17	0	1	-1	-1	-1	-1	-62.17	-57.50
6	18	0	1	-1	1	1	1	-48.83	-50.17
7	19	0	1	1	-1	1	1	-50.83	-51.67
8	20	0	1	1	1	-1	-1	-57.17	-55.33
9	5	1	-1	-1	-1	1	1	-51.83	-52.33
10	6	1	-1	-1	1	-1	-1	-50.33	-50.83
11	7	1	-1	1	-1	-1	-1	-50.67	-50.83
12	8	1	-1	1	1	1	1	-53.50	-53.00
13	21	1	1	-1	-1	1	-1	-49.83	-50.17
14	22	1	1	-1	1	-1	1	-56.50	-57.33
15	23	1	1	1	-1	-1	1	-52.50	-51.17
16	24	1	1	1	1	1	-1	-51.00	-50.83
17	9	2	-1	-1	-1	-1	-1	-55.17	-58.33
18	10	2	-1	-1	1	1	1	-65.33	-64.50
19	11	2	-1	1	-1	1	1	-64.50	-63.33
20	12	2	-1	1	1	-1	-1	-55.17	-57.83
21	25	2	1	-1	-1	-1	1	-61.00	-62.00
22	26	2	1	-1	1	1	-1	-55.00	-54.00
23	27	2	1	1	-1	1	-1	-52.50	-54.33
24	28	2	1	1	1	-1	1	-64.17	-64.67
25	13	3	-1	-1	-1	1	-1	-64.33	-63.50
26	14	3	-1	-1	1	-1	1	-61.67	-63.50
27	15	3	-1	1	-1	-1	1	-64.00	-63.67
28	16	3	-1	1	1	1	-1	-64.50	-62.33
29	29	3	1	-1	-1	1	1	-65.67	-61.17
30	30	3	1	-1	1	-1	-1	-64.67	-65.00
31	31	3	1	1	-1	-1	-1	-63.50	-64.67
32	32	3	1	1	1	1	1	-61.33	-62.67

Table 2. $4^1 2^5$ Fractionated DOE 1 matrix with response values (dBm)

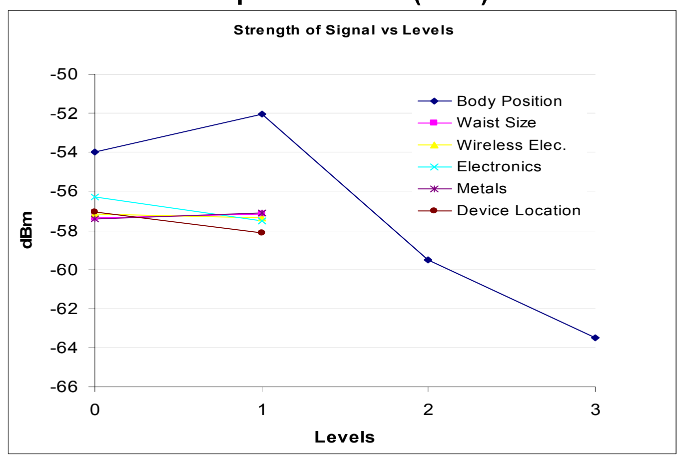

Figure 9. Main effects plot of all factors for DOE 1

Large variation was experienced with a calculated pooled standard deviation of 1.302 and confidence intervals were calculated for each effect in Table 6. A *t*-value (32 DOF at 95% confidence, $t_{32,0.05/2}$) was used to adjust for the sample size and construct the CIs. As from the plot, Table 3 shows how each factor, except factor A, have zero within their confidence intervals indicating a statistical non-significance. Further analysis of two-factor interactions was not pursued given the small magnitudes of the main effects [6].

The results show orientation of device to be the most important factor that impacts signal degradation. It's difficult to quantify the effects of the remaining factors due to their magnitudes and the variation within the experiment. A fixed body position (or constant device to receiving antenna distance) may allow better control of the transmission variation and allow a better or clearer estimate of factors 3 through 6 on signal impact. The presence of body mass drastically lowers the signal strength as seen by the change in position from 0º to 180º. In the 180º orientation, the signal must travel through the waist of the user, regardless of the slight changes in waist size, to the receiving antenna. The study suggests that wearing the device on the hip or in the pocket for the 0º and 90º positions will yield consistent high signal strength.

Factor Code	Factor Name	Effect Type	Effects	CI	
A	**Body Position (Degrees)**	Main (0-1)	-1.948	-4.606	0.710
		Main (0-2)	**5.500**	**2.842**	**8.158**
		Main (0-3)	**9.522**	**6.864**	**12.180**
		Main (1-2)	**7.448**	**4.790**	**10.106**
		Main (1-3)	**11.470**	**8.812**	**14.128**
		Main (2-3)	**4.022**	**1.364**	**6.680**
3	Body Type (Waist Size)	Main	0.181	-2.477	2.839
4	Wireless Electronics Present (Cell)	Main	-0.203	-2.861	2.455
5	Electronics Present (PDA)	Main	-1.199	-3.857	1.459
6	Metal Present (Keys)	Main	0.350	-2.308	3.008
7	Device Location	Main	-1.103	-3.761	1.555

Table 3. DOE 1 Effect estimates and confidence intervals with an α =.05

DOE 2: INVESTIGATION INTO ELECTRONIC-MECHANICAL EFFECTS ON RF SIGNAL STRENGTH

This final DOE investigates the electronic-mechanical effects on signal strength of the PS. Plastic casings were prototyped using the Fuse Deposition Modeling process conforming to a basic prismatic shape consisting of an upper and lower case. The transmission of radio waves is effected by not only electronic characteristics but also the geometry and plastic material of the casing [7,8]. The system board was secured inside the casings and oriented as depicted in Figure 10. Both the XZ and YZ planes were tested in the DOE as suggested orientations from the preliminary study. In order to increase the sensitivity of the analysis, the distance between the origin of the fixture and the TEM antenna was shortened to 1 ft.

The mechanical factors which were varied were the wall thickness of the casing and the presence or absence of metallic paint. The electronic factors which varied were the positioning of the Li-ion battery and the presence or absence of an antenna booster typically used for mobile phone antennas. The factors and factor settings are shown in Table 4.

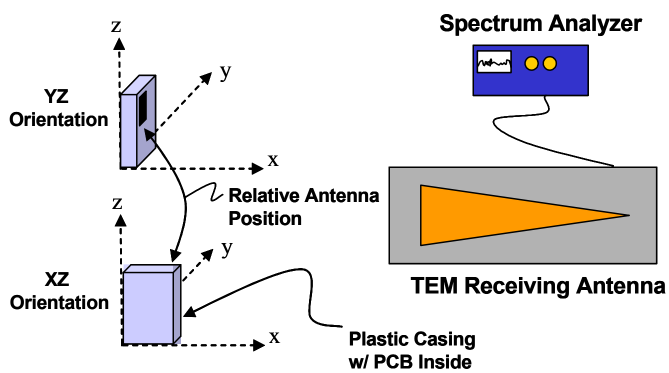

Figure 10. Experimental setup for DOE 2 with PCB inside casing

		Levels	
Code	**Factor**	**-1**	**1**
A	Battery Position	Bottom	Top
B	Antenna Booster	Not Present	Present
C	Case Thickness	0.06 in.	0.18 in.
D	Case Paint	Not Present	Present

Table 4. Factors and factor settings for DOE 2

Table 5 shows the fractionated DOE for a 2^{4-1} design with two mean response values. The experimental design has a resolution IV indicating that main effects are clear (given three factor interactions are considered negligible) and two-factor interactions are aliased with one another. Three replications were made for each test combination to calculate an estimate of error.

Test	A	B	C	D	XZ (dBm)	YZ (dBm)
1	-1	-1	-1	-1	-41.890	-44.000
2	1	-1	-1	1	-41.723	-33.777
3	-1	1	-1	1	-38.833	-40.443
4	1	1	-1	-1	-38.723	-37.223
5	-1	-1	1	1	-42.110	-41.610
6	1	-1	1	-1	-40.557	-38.390
7	-1	1	1	-1	-41.333	-43.720
8	1	1	1	1	-40.557	-37.610

Table 5. 2^{4-1} Fractionated DOE 2 matrix with mean response values (dBm)

Main effects and interaction plots are shown in Figures 11 through 15. The decibel values for strength are negative dBm. In both orientations, it was shown that when the battery was placed on top (high setting) of the PCB, meaning right near the antenna, the strength of signal increased especially in the YZ orientation (see Figure 11). The antenna booster also had the same effect when it was present but only in the XZ orientation (see Figure 11) and having no effect in the YZ orientation (see Figure 13). The case thickness reduced the signal strength as expected in both orientations as shown in both Figures 11 and 13. In the YZ orientation, the presence of metallic paint actually increased the signal strength as shown by Figure 13.

Code	Factor	Effect	CI	
A	BattPos	0.65	-0.193	1.493
B	**AntBoost**	**1.71**	**0.867**	**2.553**
C	**CaseThick**	**-0.85**	**-1.693**	**-0.007**
D	CasePaint	-0.18	-1.023	0.663
AB+CD	BattPos*AntBoost	-0.21	-1.053	0.633
AC+BD	BattPos*CaseThick	0.51	-0.333	1.353
AD+**BC**	**AntBoost*CaseThick**	**-1.32**	**-2.163**	**-0.477**

Table 6. Effects and confidence intervals for XZ plane for DOE 2

Tables 6 and 7 contain the effect estimates and confidence intervals for the XZ and YZ planes respectively. A *t*-value (16 DOF at 95% confidence, $t_{16,0.05/2}$) was used to adjust for the sample size and construct the CIs. From the results, one can interpret the proximity of the battery near the antenna as further augmenting the signal or extending the area of radiation of the antenna. This same interpretation could be used for presence of metallic paint and the associated increase in signal strength.

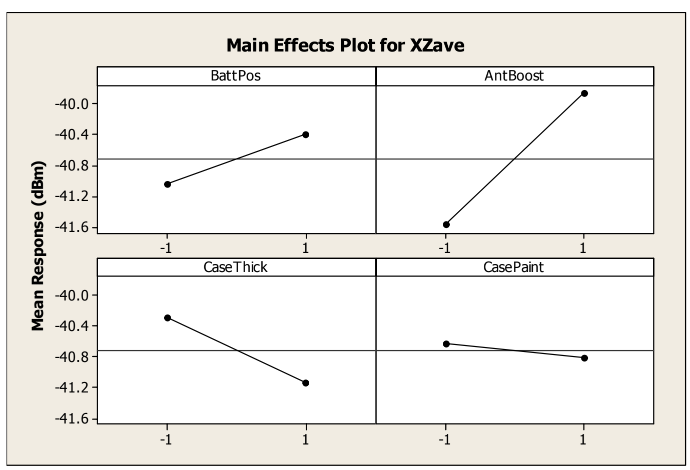

Figure 11. Main effects plot for XZ plane orientation in DOE 2

Table 6 also shows a significant effect between the interaction of two factors. There are certain principles used and have been proven by past experiments [9] in academia and industry to help in the analysis of DOEs. They are the following:

i) Hierarchical Ordering Principle:
   a. Lower order effects are more likely to be important than higher order effects
   b. Effects of the same order are equally likely to be important
ii) Effect Sparsity Principle: The number of relatively important effects in a factorial experiment is small
iii) Effect Heredity Principle: In order for an interaction to be significant, at least one of its parent factors should be significant.

The Effect Heredity Principle is employed when attributing effect estimates to confounded factors. In this case, the BC interaction is attributed to the effect estimate of -1.32 over the AD interaction since both the main effects, B and C, are active and statistically significant. Figure 12 shows the sensitivity of the Antenna Booster's effect when the Case Thickness increases, drastically reducing the signal strength.

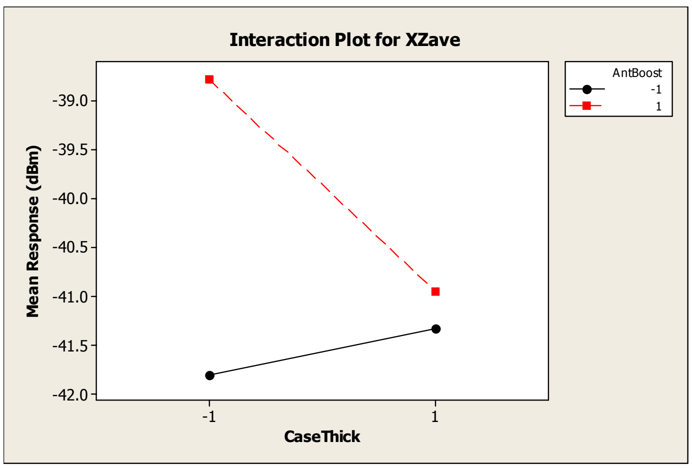

Figure 12. Interaction plot for XZ plane for AntBoost x CaseThick in DOE 2

A similar approach is taken to the interpretation of the two-interactions present in the YZ plane orientation as shown in Table 7 by the highlighted portions of the alias structure. Figure 14 shows how the Case Thickness augments the effect the Case Paint has when the plastic walls are thinner, allowing for more of the signal to pass through in addition to extending the radiation area with the presence of the paint.

Code	Factor	Effect	CI	
A	**BattPos**	**5.69**	**4.851**	**6.529**
B	AntBoost	-0.31	-1.149	0.529
C	**CaseThick**	**-1.47**	**-2.309**	**-0.631**
D	**CasePaint**	**2.47**	**1.631**	**3.309**
AB+**CD**	**CaseThick*CasePaint**	**-1.03**	**-1.869**	**-0.191**
AC+BD	**BattPos*CaseThick**	**-1.03**	**-1.869**	**-0.191**
AD+BC	BattPos*CasePaint	-0.36	-1.199	0.479

Table 7. Effects and confidence intervals for YZ plane for DOE 2

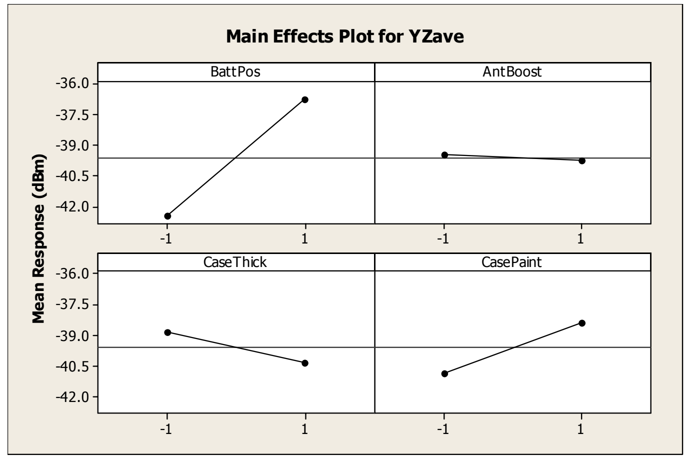

Figure 13. Main effects plot for YZ plane orientation in DOE 2

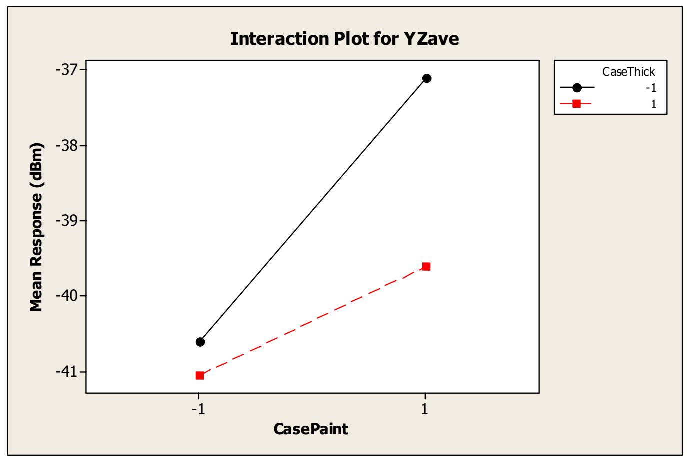

Figure 14. Interaction plot for YZ plane for CaseThick x CasePaint in DOE 2

Finally, Figure 15 shows a similar interaction but with the Battery Position interacting with the Case Thickness. As the Case Thickness increases, the augmenting effect by the Battery's proximity towards the antenna diminishes.

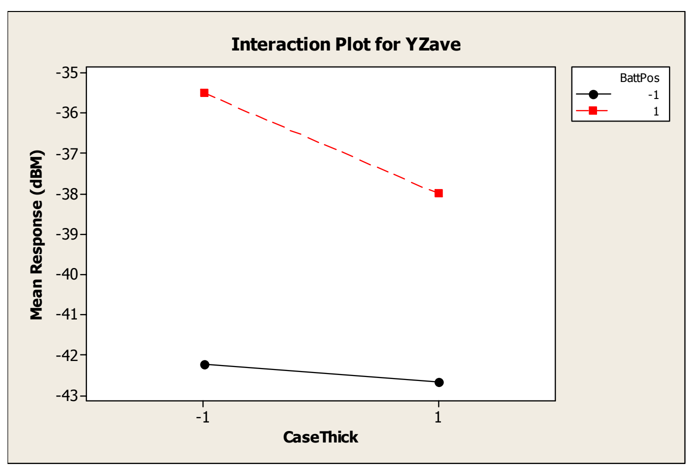

Figure 15. Interaction plot for YZ plane for BattPos x CaseThick in DOE 2

CONCLUSIONS

The results have shown that the orientation of the Personal Server to be the most important factor that impacts signal degradation. The presence of body mass drastically lowers the signal strength as seen by the change in position from 0º to 180º. The study suggests that wearing the device on the hip or in the pocket for the 0º and 90º positions will yield consistent high signal strength. The preliminary study and DOE1 indicate that a more robust signal transmission exists when the PS orients itself within the YZ plane. In addition, the drop-off study proposes an operating distance between the PS and the interfacing host to be within 5 feet.

DOE 2 drives final decisions in the geometry and coating specifications of the plastic casings where the metallic paint and thinner wall thickness were selected in the end. In order to minimized PCB volume due to component size and placement, the battery position was left on top without reducing signal strength but rather having an additive effect. Most importantly, orientation dictated whether or not certain factors would be active or not. Furthermore, the DOE 2 helped in establishing a functional relationship between the RF signal strength and factors from both the electronic and mechanical domains. The relationship is not only present but can be described quantitatively by analyzing the effect estimates. Control of the variation within the experiment is essential for utilizing such a functional relationship when interpolating for prediction or optimization.

The conclusions drawn from the experiments helped in finalizing design decisions at the PCB layout design stage for future PS versions. Mechanical design changes were also made on current and future models of the plastic casings based on findings from both design of experiments.

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