SEARCHING FOR HIGH SAR CONFIGURATIONS USING DESIGN OF EXPERIMENTS.

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INTRODUCTION: SAR measurement is time consuming; the total measurement time depends on the scan time and the number of scans needed. The scan time depends largely on the dimensions of the device under test. Testing of a larger device such as a walkie-talkie can take as long as 45 minutes for each scan. Regulatory SAR compliance requires adequate testing of many device configurations. This includes sufficient evaluation of all available accessory combinations including antennas, carry accessories, batteries and audio accessories. It is common for these devices to have many of accessories and compliance testing can take several weeks. For example, full testing of a product with 2 antennas, 4 carry accessories, 4 batteries, and 4 audio accessories would require 128 tests or roughly 100 hours of continuous testing.

OBJECTIVE: The objective of this work is to evaluate different strategies of experimentation that could be applied to reduce the number of tests needed to find the highest SAR configuration from all possible accessory combinations. Two common methods are One-Factor-At-A-Time (OFAT) and Design of Experiments (DOE) [1]. The OFAT method starts experimentation with a baseline configuration, all factors set to a particular point, and successively varying one factor while holding all other factors constant. That factor is set to the optimum (i.e., highest SAR configuration) and the next factor is varied. A deficiency of this methodology is that it does not consider any higher order interactions between the factors. A higher order interaction is an interaction that only exists under certain conditions, for example a particular antenna that produces a high SAR only when used with a particular battery but not with the other batteries. The DOE is a structured, organized method for analyzing the influence of factors and the interactions between factors on the output of a process. DOE is preferable to OFAT because it can detect the existence of higher order interactions. Detailed explanation of the methodology can be found in [1, 2]. This study demonstrates the possibility of using a DOE approach when evaluating the SAR of portable RF devices with accessories.

METHOD: Both OFAT and DOE methods were evaluated numerically. A hypothetical product with 128 possible combinations of a typical set of accessories (antennas, batteries, carry accessories, and audio accessories) was determined. Each accessory was assigned an amount of interaction it would have on the product's baseline SAR when used with the product as shown in Table 1.

Configuration Example:
A product with baseline SAR of 0.5 mW/g and using:
Antenna 2 – 30% increase
Carry Accessory 3 – 10% increase
Battery 3 – 0% increase
Audio Accessory 4 – 6% increase
Final SAR = 1.0 x 1.3 x 1.1 x 1.0 x 1.06 = 0.758 W/kg.

Table 1: Example of a wireless device with two antenna types, four carry accessory types, four battery types and four audio accessory types.

Accessory	#	Influence on SAR from baseline configuration
Antennas	1	0%
	2	30%
Carry accessories	1	30%
	2	0%
	3	10%
	4	20%
Batteries	1	0%
	2	0%
	3	0%
	4	30%
Audio accessories	1	4%
	2	2%
	3	0%
	4	6%

Interactions were intentionally selected to test the ability of the methods to catch the maximum configuration for varying conditions. In this hypothetical product, the antenna, carry accessory, and battery had the highest potential for influence on SAR. The battery interaction was selected so only one specific battery would cause an interaction. Initially, higher order interactions were not incorporated. The final SAR of the product and accessory combination is determined modifying the baseline SAR by the influences the accessory combination as shown in the example. The ability of both methodologies to determine the highest SAR configurations was evaluated using this model.

RESULTS:

One-Factor-At-A-Time (OFAT) example

The model of Table 1 can be implemented as seven two-level (binary) factors. Antenna type is one two-level factor (A = -1 for antenna 1; A = +1 for antenna 2). The four carry accessory types can be expressed as two binary factors (BC = -1-1, -1+1, +1-1 and +1+1). Similarly, the four battery types and four audio accessories can be expressed as two binary factors (DE and FG, respectively). For this example, a full factorial design (all possible combinations) would 2^7 or 128 tests. However, a considerable amount of knowledge can be gained from fewer tests. To run an OFAT experiment, each factor is varied in sequence. An example of this is shown in Table 2, where each factor was varied in the following order: antenna type, then carry accessory type, then battery type, then audio accessory type. The max result was found in test #9 with a SAR of 1.5W/kg.

Table 2: SAR results of the OFAT example.

Test	A	B	C	D	E	F	G	SAR (W/kg)
1	-1	-1	1	-1	-1	1	-1	0.60
2	1	-1	1	-1	-1	1	-1	0.78
3	1	1	-1	-1	-1	1	-1	0.86
4	1	1	1	-1	-1	1	-1	0.94
5	1	-1	-1	-1	-1	1	-1	1.01
6	1	-1	-1	-1	1	1	-1	1.01
7	1	-1	-1	1	-1	1	-1	1.01
8	1	-1	-1	1	1	1	-1	1.42
9	1	-1	-1	1	1	1	1	1.50
10	1	-1	-1	1	1	-1	-1	1.48
11	1	-1	-1	1	1	-1	1	1.45

Design of Experiments (DOE) example

This example will use a fractional factorial design with 2^4 = 16 tests. To do this, the first four factors (A, B, C and D) will be varied in all combinations, while the remaining three factors will be assigned to combinations of the first four. The design chosen here is E = ABC, F = BCD and G = ACD (the values of E, F and G are determined by multiplying the values of A, B, C and D together).

Suppose that the baseline configuration (antenna 1, carry accessory 2, battery 1 and audio accessory 3) gives an SAR of 0.5 W/kg. The 16 tests from this DOE and the resulting SAR values from the model of Table 1 are shown in Table 3. In practice, tests are run in random order [1] to help minimize any time variant effects.

Table 3: SAR results of the DOE example.

Test	A	B	C	D	E	F	G	SAR (W/kg)
1	-1	-1	-1	1	-1	1	1	0.83
2	-1	1	1	-1	-1	-1	1	0.73
3	1	-1	-1	-1	1	-1	1	1.03
4	1	1	1	-1	1	-1	-1	0.97
5	1	-1	1	-1	-1	1	-1	0.78
6	-1	1	-1	-1	1	1	-1	0.66
7	-1	1	-1	1	1	-1	1	0.94
8	1	1	-1	-1	-1	1	1	0.91
9	1	1	-1	1	-1	-1	-1	0.89
10	1	1	1	1	1	1	1	1.39
11	-1	-1	1	-1	1	1	1	0.64
12	-1	-1	1	1	1	-1	-1	0.87
13	1	-1	1	1	-1	-1	1	0.80
14	-1	1	1	1	-1	1	-1	0.72
15	-1	-1	-1	-1	-1	-1	-1	0.81
16	1	-1	-1	1	1	1	-1	1.42

One important issue to consider is that assigning some factors to combinations of other factors results in "aliasing". The aliasing table for this design is shown in Table 4. Each row of the table shows which factors are aliased (in DOE notation, '+' means 'is aliased with'). For example, E is aliased with ABC (which should be obvious, since it was set up that way). This means that if an influence is detected, one cannot differentiate whether the influence is caused by E (half of the battery combinations), ABC (an interaction between antennas and carry accessories), or any of the other factors shown in the corresponding row of the alias table. For this reason, it is important to review the aliasing table and ensure that important factors and interactions are only aliased with interactions that are unlikely to be significant. In general, interactions with more than two or three factors are not likely to be significant [1].

Table 4: Aliasing table for the example DOE.

A + BCE + BFG + CDG + DEF + ABCDF + ABDEG + ACEFG
B + ACE + AFG + CDF + DEG + ABCDG + ABDEF + BCEFG
C + ABE + ADG + BDF + EFG + ABCFG + ACDEF + BCDEG
D + ACG + AEF + BCF + BEG + ABCDE + ABDFG + CDEFG
E + ABC + ADF + BDG + CFG + ABEFG + ACDEG + BCDEF
F + ABG + ADE + BCD + CEG + ABCEF + ACDFG + BDEFG
G + ABF + ACD + BDE + CEF + ABCEG + ADEFG + BCDFG
AB + CE + FG + ACDF + ADEG + BCDG + BDEF + ABCEFG
AC + BE + DG + ABDF + AEFG + BCFG + CDEF + ABCDEG
AD + CG + EF + ABCF + ABEG + BCDE + BDFG + ACDEFG
AE + BC + DF + ABDG + ACFG + BEFG + CDEG + ABCDEF
AF + BG + DE + ABCD + ACEG + BCEF + CDFG + ABDEFG
AG + BF + CD + ABDE + ACEF + BCEG + DEFG + ABCDFG
BD + CF + EG + ABCG + ABEF + ACDE + ADFG + BCDEFG
ABD + ACF + AEG + BCG + BEF + CDE + DFG + ABCDEFG

The interaction plot of this DOE is shown in Fig. 1. Cells that have very different lines (different slopes or offsets) indicate interactions. These effects are also quantified by the *p* value (Table 5), a *p* value less than 0.05 indicates significance [1] and are highlighted in the table. From Fig. 1 and Table 4, it can be seen that the antenna type, carry accessory type and battery type have a strong effect on SAR, while the audio accessory type does not have a strong effect (p value 0.061). An analysis of the two-factor interactions indicates that only BC (carry accessory types) and DE (battery types) are significant. These are not really interactions; they just show the variability between carry accessory types and battery types. All other interactions are not significant (the apparent interactions of AE, AF, DF and BG in Fig. 1 are really due to aliasing with BC, DE, BC and DE, respectively, as can be seen in the aliasing table). This is expected, since higher order interactions were not included in this example.

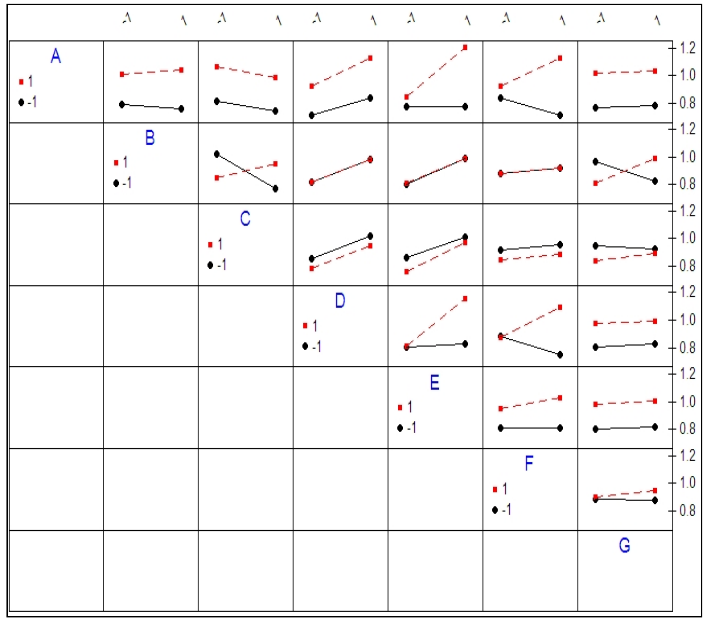

Fig. 1: Plot of two-factor interactions of the example DOE.

Since there are no significant higher order interactions, picking the highest combination from interaction plot should give the highest SAR. From Fig. 1, it is seen that this corresponds to A = +1 (antenna 2), BC = -1-1 (carry accessory 1), DE = +1+1 (battery 4) and FG = +1+1 (audio accessory 4). This agrees with the model in Table 1. Thus, the DOE correctly determined the highest SAR combination, even though it did not directly measure it. The next step is to measure the highest SAR combination for confirmation.

If there are no higher order interactions (as in this case), the OFAT experiment will always find the highest combination. However, there is no way of knowing with an OFAT whether or not higher order interactions exist. This is the disadvantage compared to the DOE. If a possible higher order effect is seen in the DOE, a subsequent DOE is necessary to isolate it.

Table 5: p value of main factor and two-factor interactions of the example DOE.

Main factors		Interactions	
Term	P	Term	P
A	**0.010**	AB	0.083
B	0.500	AC	0.500
C	**0.032**	AD	0.066
D	**0.014**	**BC**	**0.014**
E	**0.013**	**DE**	**0.015**
F	**0.061**	AG	0.795
G	0.126	BD	0.795

Higher Order Interactions

The OFAT required 11 tests to complete the evaluation of the example above. The DOE required 17 tests but when higher order interactions were introduced the OFAT is unable to detect those configurations in a consistent matter. Higher order interactions can only be detected by OFAT if the original test plan tests the configuration with the higher order interaction by coincidence. Even then, complete evaluation of the interaction is unlikely. This is shown by using an incremental approach, where both methodologies were compared when evaluating an increasing higher order interaction. Depending on the magnitude of the higher order interaction, this can lead to large errors in determination of high SAR configurations.

In our example, a battery with a higher order interaction was introduced. The actual SAR (the blue curve) becomes influenced by the higher order interaction

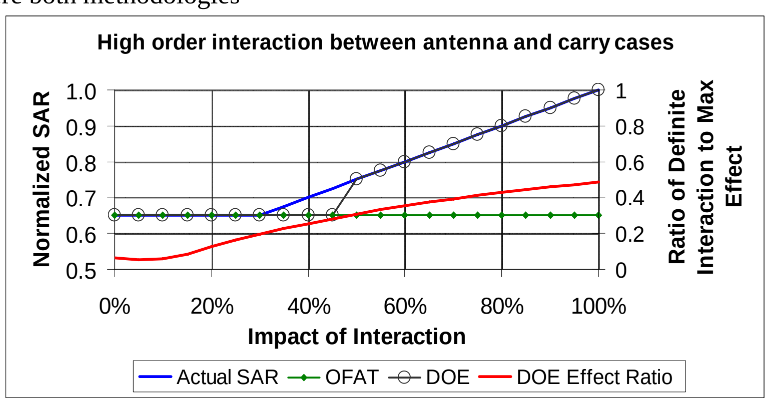

Figure 2 – DOE sensitivity to higher order interactions.

when it increases beyond the influence on SAR of battery #4 (+30%). The DOE (black curve with circular markers) cannot detect the higher order interaction until it becomes somewhat significant. The Effect Ratio (a measure in the confidence of the determination of an interaction and calculated as ratio between the suspected effect to the max effect seen in the evaluation) also increases as the interaction increases. The factors of this example were intentionally selected to be transparent to the OFAT, as shown by the green OFAT curve.

Impact of Measurement Uncertainty

SAR measurement has a large measurement uncertainty. The robustness of the DOE to measurement uncertainty was evaluated by using a Monte Carlo evaluation. Uncertainty was generated by randomly selecting a value from a normal distribution with known standard deviation and was added to each DOE test to simulate measurement uncertainty.

Using the example above:
A product with baseline SAR of 0.5 W/kg and:
Antenna 2 – 30% increase
Carry Accessory 3 – 10% increase
Battery 3 – 0% increase
Audio Accessory 4 – 6% increase
Final SAR = Uncertainty x 1.0 x 1.3 x 1.1 x 1.0 x 1.06 = 0.758 W/kg.

The DOE evaluation was performed and the result was compared with the expected value. The results are shown in Figure 3.

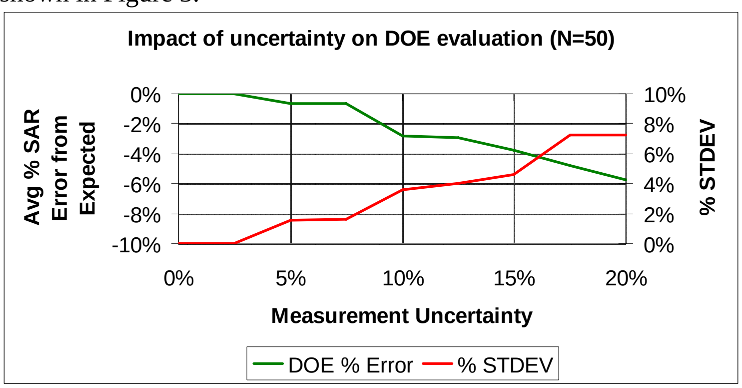

Figure 3 – Impact of uncertainty on DOE.

It can be seen that for large uncertainties, the DOE can determine high SAR conditions fairly well.

CONCLUSION: Since the existence of higher order interactions for products and accessories is unknown, it is possible that high SAR configurations could be missed by the OFAT approach. The DOE method is preferable because it can detect these interactions without significantly increasing test time.

REFERENCES:

[1]. D. Montgomery. “Design and Analysis of Experiments, Fifth Edition.” John Wiley and Sons, City and State, 2001.
[2]. K. Hinkelmann, O. Kempthorne. “Design and Analysis of Experiments, Volume 1” John Wiley and Sons, City and State, 1994.