Robustness comparison of Bow-tie and Dipole antennas

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Abstract— Present paper describes application of a computer intensive methodology to evaluate antenna susceptibility to random physical damage for a Dipole and a Bow-tie antenna. For each randomly generated damage pattern antenna parameters are simulated and statistical comparison is performed.

Computer intensive statistical methods like the Bootstrap used for the post processing make fewer initial assumptions than classical statistical methods when modeling a problem, and are robust against small deflections from these assumptions. The Bias-Corrected and accelerated (BC_a) Bootstrap method is used for confidence interval estimates.

The Dipole antenna is found to be more robust to numbers of small (~100^{th} of a wavelength) circular holes penetrating the structure than the Bow-tie.

1. INTRODUCTION

In some applications an antenna is expected to work even when its structure has been partially damaged. One obvious example is military applications like armour integrated antennas, where functionality should degrade gracefully even if the antenna is partially damaged by splinters or fine calibre fire. Another example is low cost transceivers (tags) used for Radio Frequency IDentification (RFID) where the need to keep antenna manufacturing costs down is accomplished through printing of conductors [1] directly upon very low-cost substrates, like paper. One way to reduce the tag cost is to use a minimal amount of conducting ink when printing the antenna structure. However, if the substrate is relatively coarse and the paint is applied too thinly, areas where the paint does not fully cover the substrate or is easily rubbed away, might occur. For both the military case and the RFID case the antenna structures thus could contain fissures that may affect the antenna performance.

In order to compare antennas from the damage tolerance point of view a Monte Carlo statistical methodology is used to estimate vital antenna parameters for different damage levels. Previous investigation on antenna structural damage has primarily been directed towards antenna arrays and parabolic antennas [2]-[15] ([16] is more general) using classical statistical theory. In present paper a Dipole antenna is compared with a Bow-tie antenna in their ability to handle physical damage in the form of small circular holes. The Dipole and Bow-tie where chosen due to the fact, that their basic dimensions are close and yet some small differences in the layout lead to differences in damage tolerance. Another reason is that simple antennas such as the Dipole and Bow-tie need less computer time for parameter simulations as compared to more complex structures.

2. METHODOLOGY

2.1. General

The approach is based upon a comparison of performance of antennas with randomly inflicted damage positioned at a random, all over the structure. A commercial electromagnetic field simulation software package is used to analyze the parameters of antenna structures, both damaged and undamaged. This software should have a flexible Computer Aided Design (CAD) capability to construct the antenna structure. The software should also contain some scripting capability to allow random positioning of the holes in the structure (damages), simulating the inflicted damage. Modern electromagnetic field simulators (EM-simulators) commonly provide a variety of antenna parameters that can be used for performance assessment. Data yielded by the antenna modeling software is treated with statistical methods to conclude how vulnerable to certain type of damage a particular antenna is by itself, or compared to other antennas in a survey.

2.2. Monte Carlo antenna simulation

The Monte Carlo method is a computer-based random sampling approach for approximate solving of problems concerned with a complex system [17]. Presently the positions of the damages are randomized in a "working field" and the antenna performance is simulated by CST Microwave Studio (MWS) 4.0 [18]. This software has the ability to use Visual Basic scripts [19] for program control. The damages inflicted on the antenna are modelled as circular holes through the structure orthogonal to the planar surface of the antennas. The simulation data is saved as an ASCII-file for subsequent statistical processing.

The simulation data from MWS is processed in Matlab with the aid of the Matlab Statistics Toolbox [20]. A "buckshot" approach, inflicting more than one damage each time, rather than making statistics for one "hail" at a time is chosen due to the large number of simulations and the estimated computer time required for such task. The Matlab program calculates the Bootstrap statistics for each of the two (bowtie and dipole) antennas. (The Matlab Statistics Toolbox contains a "Bootstrap command" which helps to reduce the programming effort for a Bootstrap analysis.). Fig. 1. illustrate the generation of the "working field" for antenna damage simulations. Maximum damage length, l_d, and Maximum damage height, l_h, are equal to the diameter of the circular holes, covering the shape of a particular selected damage. A priori knowledge is thus required of Maximal Damage Length, Maximal Damage Height, antenna structure Maximal Length l_n

and Maximal Height h_n, for each antenna (n = 1...N, where N is the total number of antennas).

A rather dense meshing is needed for the correct EM simulations whereas two holes can occur close to each other, leaving a very thin bridge of conducting material between them. For each damage case the antenna parameters are calculated using EM modelling software. To ensure a valid statistical comparison of antennas from this respect, several randomly damaged antennas have to be considered. Trail for at least 25 structures with different damage has been found to give sufficient data for good statistical analysis.

2.3. Statistical Post Processing

Computer intensive statistical methods like Bootstrap used in the post processing make fewer assumptions than classical statistical methods when modeling a problem, and are robust against small deflections from these assumptions [17]. The Bootstrapping statistical inference method [17], [21] is attractive for the cases when the underlying statistical distribution is unknown or non-Gaussian [22]. So when using the Bootstrapping methodology it is not necessary to make assumptions regarding the input data, because the method is based on multiple resampling of collected data.

An asymmetric confidence interval is desirable to determine how good (or bad) an estimate is since there might be large deviations if, for instance, a parameter goes to zero or infinity when a damage occurs at the antenna feed. In this comparison the BC_a method for (asymmetric) confidence interval is used. A description of the Bootstrapping methodology used in this paper can be found in Appendix 1.

3. COMPARISON OF DIPOLE AND BOW-TIE ANTENNA ROBUSTNESS

3.1. Setup

Both undamaged antennas are designed to operate at 2.45 GHz (one of the Industrial, Scientific and Medical, ISM, frequency bands often used for RFID applications). The median value is studied for each output parameter to get the "typical" behaviour of the antenna even if there are outliers (stray values) in the simulation data. The outliers arise when damage occurs in a vital part of the antenna, i.e. at the antenna feed. The antennas are modelled as Perfect Conductors (PEC) placed in free space, without any supportive substrate. Damage is chosen to be represented by a set of round holes having identical diameter. This limitation could seem rather restrictive, as actual damage holes can have very different shapes. But if the hole sizes (characteristic hole dimensions) are much smaller than the wavelength (characteristic antenna dimensions) actual current density distribution in the flat conductor with a "non-regular" hole and round hole, entirely enclosing this non-regular shape can be expected much the same, thus leading to very close antenna parameters.

Following parameter values are chosen for damage robustness assessment of the dipole and bow-tie antennas:

Antenna conductor thickness:	0.1 mm
Damage hole radius:	0.61 mm (diameter is $\lambda/100$ at 2.45 GHz)
Feed gap:	2.0 mm
The "imaginary" frame:	55.52 x 11.92 mm (for both antenna types)

3.1.1. Bow-tie antenna

The Bow-tie antenna designed to operate at 2.45 GHz has an arm length of 20.0 mm and a flare angle of 30 degrees which gives a maximum height of the structure of 10.7 mm and a total area of 214 mm^2. The input impedance: 47 Ohms for resonance.

3.1.2. Dipole antenna

The dipole antenna has an arm length of 26.15 mm and a height of 4.1 mm and thus a total area of 214 mm^2. The input impedance: 65 Ohms for resonance.

3.2. Results

Fig 2. show two models for the Bowtie antenna a) without any damage, and b) when the antenna has been damaged by multiple round holes of identical diameter. This figure illustrates why the working frame should be larger, at least by one damage diameter, than the largest antenna dimension in all directions. The "light touches" of some hails, like the one in upper left corner of left antenna arm in Fig. 2. (b), must be accounted for in order to ensure a realistic damage influence assessment. Making the frame larger will just increase computing time, as the larger number of damage holes will miss antenna structure altogether.

Depending on where the damages hit within the working area the remaining antenna area will differ even between structures exposed to the same number of damages. The sample values with close antenna area are grouped together (in 20 bins) and the median is calculated for the corresponding antenna parameter values. Error bars show the confidence intervals of the data at the median points. The median points are connected by a curve. The confidence intervals are acquired using the BC_a method with a Bootstrap sample size of B=10000 for the confidence intervals. The chosen confidence level is 90% and 25 (differently) damaged structures for each antenna type was used to get significant sampling space for comparison. Confidence intervals are still relatively wide due to the number of structures and the confidence level used though it is enough to see major trends. The number of damaged structures to use for simulation is a compromise between accuracy and computer time.

Regarding antenna performance it is of interest to study the transition zones from full functioning antenna to a completely destroyed antenna where the antenna parameter values can fluctuate, and how much fluctuation can be expected at a certain confidence level. It is possible to create narrower confidence intervals by removing outliers in the statistical data, i.e. simulations where damage occurs at the input terminals at one of the first “buck shots” of a simulation. This would however remove some useful information while it is interesting to know how often “fatal” damage occur for a certain structure. Compared with the average statistic the median statistic gives wide confidence intervals, but without information being lost.

3.2.1. Input Return Loss

The Input Return Loss (S_{11}) is plotted versus antenna area for the Dipole and the Bow-tie antennas in Fig. 3. (The undamaged antennas are matched to their feed.) The plot show that the Bow-tie can not handle any larger amount of damage before the S_{11} curve moves into a transition zone where the confidence interval comprises the zero level which gives a total loss in the interface between the antenna and the feed. The Dipole antenna S_{11} curve also raise swiftly for minor damage, but the growth is not as rapid as for the Bow-tie antenna after the initial loss of structure area.

The S_{11} show the antenna behaviour from the antenna input terminal point of view. Obviously the Bow-tie antenna gets mismatched quicker than the Dipole antenna. The probability of the Dipole antenna having at least some match with the input terminal remains for quite large antenna area loss.

3.2.2. Bandwidth shift

Fig. 4. illustrate a typical situation, when damaged antenna “working frequency interval” is offset as compared to the one of the undamaged antenna. Under the assumption that a communication system was designed to use exactly the frequency range Δ defined by undamaged antenna parameters (i.e. VSWR ≤ 2), damaged antenna would be able to cover only smaller part of initial frequency range $\delta < \Delta$ because of the “tuning frequency” offset and VSWR degradation. In order to compare the severity of the antenna damage inference upon the communication system the effective bandwidth parameter $BW = 100 * \frac{\delta}{\Delta}$ is introduced. BW = 100% thus means no damage inference whatsoever and BW = 0% is complete loss of antenna functionality as regarded to chosen communication system.

The bandwidth shift is plotted versus antenna area for the Dipole and the Bow-tie antenna in Fig. 5. For the Dipole only a smaller shift in bandwidth can be expected until the antenna area has dropped below 175 mm^2. Below this point the bandwidth for the Dipole antenna moves into a transition zone. The Bow-tie antenna bandwidth keep stabile until a transition zone from 190 mm^2 down to about 180 mm^2 antenna area emerges. Below this transition zone no remnants of the original Bandwidth can be expected.

3.2.3. Maximum Directivity

The Maximum Directivity is plotted versus antenna area for the Dipole and the Bow-tie antenna in Fig. 6. The Directivity for the undamaged Dipole- and Bow-tie antennas is not high. They both produce a “doughnut”-shaped radiation pattern and have thus no preferred main lobe direction. The effect of structural damage gives minor change of the maximum directivity for both antennas.

4. CONCLUSION

In this paper it was shown that the Dipole antenna is more robust than the Bow-tie antenna against randomly placed circular holes inflicted upon it. The area close to the antenna feed is expected to have maximum influence on antenna performance due to the strong current density experienced there [23]. It seems like the Bow-tie input terminals with a sharp apex angle gives an increased vulnerability to damages of this type rather than the (flat) Dipole input terminals connecting on the short end of a wider antenna structure.

The evaluation was made by a computer intensive Monte Carlo approach that incorporated computer generated antenna simulation, computer generated random damage to the “CAD”-structure and Bootstrap statistics for the statistic post processing.

Future work will show if (how) the size and shape of the damages affect antenna performance for the antenna geometries investigated.

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6. APPENDIX

This chapter is based on bootstrap methodology outlined in [17]. A random sample $\boldsymbol{x} = (x_1, x_2, ..., x_n)$ from an unknown probability function F is observed and the sought parameter θ is estimated. An estimate of θ is

$$\hat{\theta} = s(\boldsymbol{x}), \tag{2}$$

where $s(\boldsymbol{x})$ is a *statistic* – a function of the sample $\boldsymbol{x}$. If $\hat{F}$ is the empirical distribution with probability $1/n$ on each of the observed x_i, $i = 1, 2, \ldots, n$, a bootstrap sample is defined as a random sample of size n drawn from $\hat{F}$, say $\boldsymbol{x}^* = (x^*_1, x^*_2, ..., x^*_n)$, $\hat{F} \rightarrow (x^*_1, x^*_2, ..., x^*_n)$.

In other words, the bootstrap data points $x^*_1, x^*_2, ..., x^*_n$ are a random sample of size n drawn with replacement from the population of n objects $(x_1, x_2, ..., x_n)$. The bootstrap data set $(x^*_1, x^*_2, ..., x^*_n)$ consists of members of the original data set $(x_1, x_2, ..., x_n)$, some appearing zero times, some appearing once, some appearing twice, etc.

The star notation indicates that the bootstrap data set $\boldsymbol{x}^*$ is not the actual data set $\boldsymbol{x}$, but rather a randomized, or *resampled*, version of $\boldsymbol{x}$. The Bootstrap replication of $\hat{\theta}$ for the bootstrap data set $\boldsymbol{x}^*$ is

$$\hat{\theta}^* = s(\boldsymbol{x}^*). \tag{3}$$

In this paper $s(\boldsymbol{x})$ is the median. A selection of B independent bootstrap samples $x^{*1}, x^{*2}, \ldots, x^{*B}$, each consisting of n data values drawn with replacement from $\boldsymbol{x}$ are evaluated with

$$\hat{\theta}^*(b) = s(\boldsymbol{x}^{*b}), \tag{4}$$

b= 1,2,...,B for each bootstrap sample b. The value B is dependent on the type one whishes to perform. For the BC_a method (below) it is suggested to use B>1000 to reduce the bootstrap sampling error (a higher number makes for smaller errors).

The BC_a (Bias-Corrected and accelerated) method for confidence intervals is second order accurate and transformation respecting. This means that for the BC_a method the errors go to zero rapidly in terms of the sample size and that the BC_a endpoints transform correctly for a change of the parameter θ to a function of θ.

An interval of intended coverage $1-2\alpha$ (nominal confidence level) is given by $(\hat{\theta}^{*(\alpha_1)}, \hat{\theta}^{*(\alpha_2)})$,

$$\alpha_1 = \Phi\left(z_0 + \frac{\hat{z}_0 + z^{(\alpha)}}{1-\hat{a}\left(\hat{z}_0 + z^{(\alpha)}\right)} \right) \tag{5}$$

and

$$\alpha_2 = \Phi\left(z_0 + \frac{\hat{z}_0 + z^{(1-\alpha)}}{1-\hat{a}\left(\hat{z}_0 + z^{(1-\alpha)}\right)} \right). \tag{6}$$

$\Phi(\cdot)$ is the standard normal cumulative distribution function where $\hat{z}^{(\alpha)}$ is the 100α th percentile point of a standard normal distribution and $\hat{z}_0$ is the Bias-correction

$$\hat{z}_0 = \Phi^{(-1)}\left(\frac{\#\left\{\hat{\theta}^*(b) < \hat{\theta}\right\}}{B} \right). \tag{7}$$

(The notation $\#\{x_i < \theta\}$ means the number of x_i s less than θ and $\Phi^{-1}(\cdot)$ is the inverse standard normal cumulative distribution function.)

To determine the acceleration term the *jackknife* [17] technique can be implemented. This method uses samples that leave out one observation. However, when using the median for $s(\boldsymbol{x})$ the jackknife is not consistent. A way to achieve consistency is to remove more than one observation. The number of sample points left out: d, must be within the interval $\sqrt{n} < d < n$, where n is the total number of observations. Using the bootstrap methodology on the jackknife lessens the burden of drawing all possible combinations of samples. A random sequence of sample points are drawn many times instead. So

$$\hat{a} = \frac{\sum_{s=1}^{m}\left(\hat{\theta}_{(\cdot)} - \hat{\theta}_{(s)}\right)^3}{6\left(\sum_{s=1}^{m}\left(\hat{\theta}_{(\cdot)} - \hat{\theta}_{(s)}\right)^2\right)^{3/2}} \tag{8}$$

is the acceleration term, which relates to the rate of change of the standard error of $\hat{\theta}$ in (2) with respect to the true parameter value θ.

Let $\boldsymbol{x}_{(s)}$ be the original sample with the subset s deleted and m the number of random sequences to be drawn.

$$\hat{\theta}_{(s)} = s\left(\boldsymbol{x}_{(s)}\right) \tag{9}$$

$$\hat{\theta}_{(\cdot)} = \sum_{s=1}^{m} \frac{\hat{\theta}_{(s)}}{m} \tag{10}$$

The above is a bootstrap influenced modification of the jackknife technique for estimating the bias and standard error of an estimate.

7. LIST OF CAPTIONS TO ILLUSTRATIONS

8. FIGURES

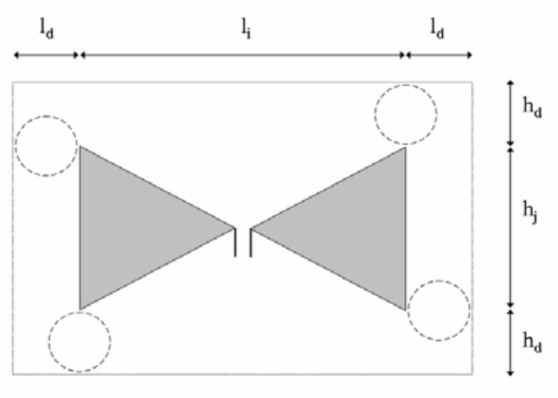
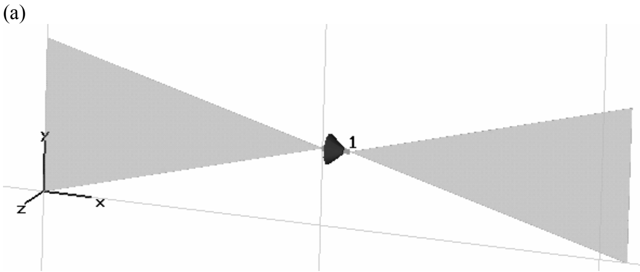


Fig. 1.

(a)



(b)

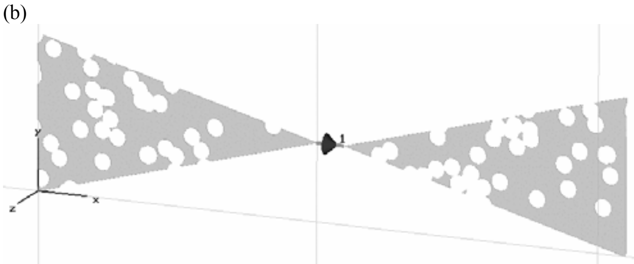
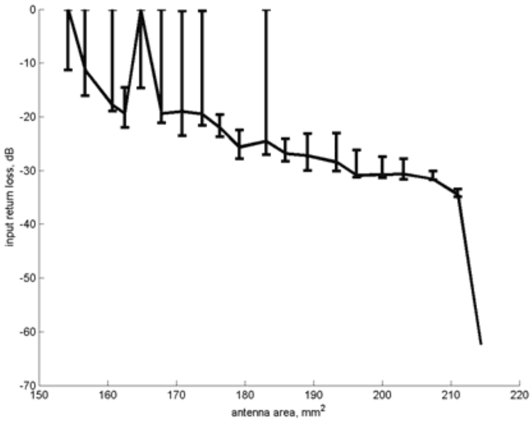
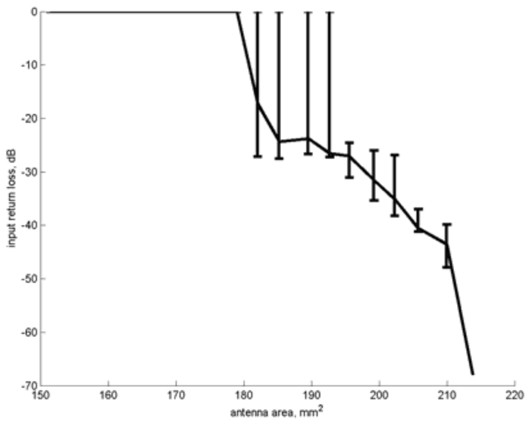


Fig. 2.



input return loss, dB
0
-10
-20
-30
-40
-50
-60
-70
150
160
170
180
190
200
210
220
antenna area, mm^2



input return loss, dB
0
-10
-20
-30
-40
-50
-60
-70
150
160
170
180
190
200
210
220
antenna area, mm^2

Fig. 3. (a) (b)

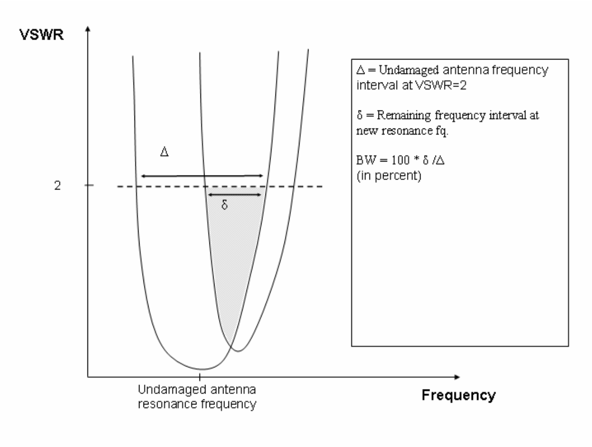

VSWR
2
Δ
δ
Undamaged antenna
resonance frequency
Frequency
Δ = Undamaged antenna frequency interval at VSWR=2
δ = Remaining frequency interval at new resonance fq.
BW = 100 * δ /Δ
(in percent)

Fig. 4.

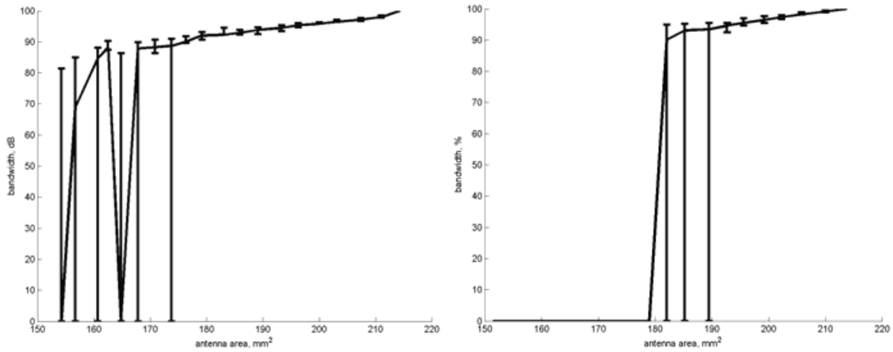
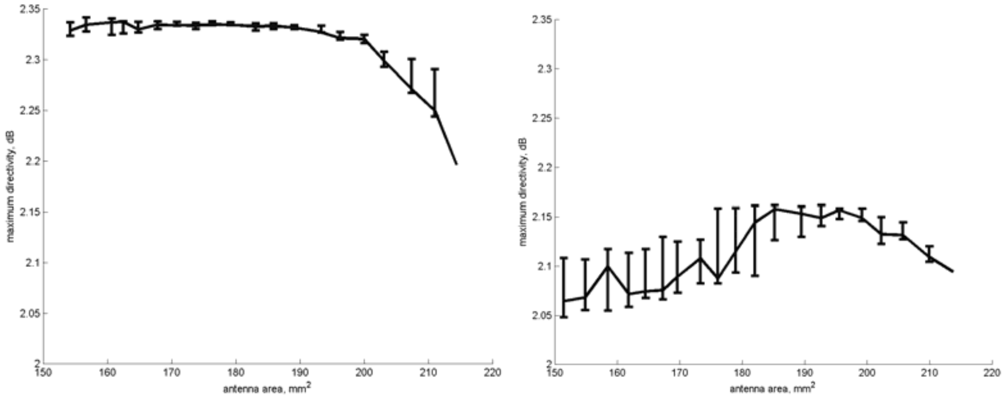


Fig. 5. (a) (b)



2.35
2.3
2.25
2.2
2.15
2.1
2.05
2
150
160
170
180
190
200
210
220
maximum directivity, dB
antenna area, mm2

Fig. 6. (a) (b)