Aircraft Antenna Coupling Minimization Using Genetic Algorithms and Approximations

Genetic algorithms (GAs) are used to minimize antenna coupling by optimally positioning multiple radiators. Initial GA parameters are selected using a simple cylindrical model, and the results are used to optimize antenna placement on a realistic aircraft surface model. A novel aggregate objective function incorporating surface wave coupling, variance of the coupling values, and radiation pattern analysis is used. Multiple computational and experimental data are shown to validate the methodology.

I. INTRODUCTION

The communication and navigation capabilities of modern military and civil aircraft are broad and diverse, requiring many antenna apertures that operate in overlapping frequency bands. When combined with limited usable real-estate on an aircraft surface, system-to-system interference can quickly reach intolerable levels. Before resorting to adaptive filtering, system blanking or simply turning incompatible systems off, maximum care should be taken to select antenna positions that minimize electromagnetic coupling. This problem statement has applicability in the design stage (e.g., when positioning many antennas simultaneously) and in a sustainment and support scenario (e.g., when adding a new antenna system with fixed existing apertures). The optimum arrangement results in the lowest realizable antenna-to-antenna electromagnetic coupling. This problem statement has applicability in the design stage (e.g., when positioning many antennas simultaneously) and in a sustainment and support scenario (e.g., when adding a new antenna system with fixed existing apertures). The optimum arrangement results in the lowest realizable antenna-to-antenna electromagnetic coupling (i.e., most favorable electromagnetic interference (EMI) environment) based solely on physical antenna positioning. This must be accomplished without undue degradation of antenna performance, such as angular and polarization coverage. Then, if required, additional passive, active, or filtering techniques may be applied to select systems or apertures requiring further interference reduction.

With the above problem scenario in mind, the designer must determine what fidelity of electromagnetic modeling is practical for an optimization of many variables. With global optimization the goal, it is understood that many possible antenna arrangements will require evaluation making first principle computational electromagnetic techniques (e.g., moment method) time prohibitive or impossible to implement on large aircraft. To optimize in such a case, innately faster asymptotic techniques can be applied to the problem until convergence is approached and then higher fidelity techniques can be applied practically. In a first-principle solution, all coupling mechanisms are combined and are not separable. In contrast, asymptotic techniques calculate the coupling mechanisms separately and the researcher must determine the number and type of interactions to include in the solution. In this project, it is assumed that the primary coupling mechanism in an optimal antenna arrangement will be the surface diffracted wave coupling mechanisms and is therefore the focus of this effort.

We demonstrate a technique for optimally positioning multiple antennas operating in the very high frequency (VHF, 150–300 MHz) band on a Boeing 747-200 aircraft using genetic algorithms (GAs) [1–6]. Initially, a simple right circular cylinder is used to model the fuselage of the Boeing 747-200 aircraft where the techniques are demonstrated and validated before applying them in a more complicated scenario with a realistic aircraft geometry (see Fig. 1). When applied in the more complex case, the parameterizations leading to the best results from the cylinder experiments are used. Simple GA, micro-GA and GA population seeding techniques are all used and compared with an exhaustive GA/local search benchmark.

1The global optimum is the “best” point in the design space, while a local optimum is the “best” point in some subset of the design space.
II. ELECTROMAGNETIC COUPLING AND UNIFORM THEORY OF DIFFRACTION TECHNIQUES

Coupling is typically described by a decibel value of the ratio of coupled to transmitted power [7]:

\[ C = 10 \log_{10} \left( \frac{P_r}{P_t} \right) \]  \hspace{1cm} (1)

where \( P_r \) is power transmitted by one onboard antenna and \( P_t \) is the received power at another (victim), antenna. Beyond simple audible interference, antenna coupling can distort the victim antenna’s radiation pattern and/or change its driving point impedance resulting in inefficiency or damage to the victim receiver [7]. Rather than calculate coupled power based on the coupled current distribution and driving point impedance, one may use the uniform theory of diffraction (UTD) [8] coupled electric field solution

to determine the amount of electromagnetic coupling between two antennas.

A. Surface Wave Coupling

UTD can be used to predict surface wave coupling on convex, perfect-electric conducting (PEC) surfaces. The surface waves follow Keller’s geodesic paths from the source to the victim antenna [9]. Pathak and Wang [10] developed expressions for surface wave coupling for monopoles and slot apertures for arbitrary smooth convex structures based on Keller’s geometrical theory of diffraction (GTD) framework [9]. Their work expanded and enhanced previous surface wave work by including higher order terms in the underlying asymptotic expansion and modeling the effects of surface ray torsion, leading to improved accuracy with little additional computational cost.

The incremental current for an electric monopole of strength \( I \) at some angle relative to the surface normal \( \hat{n} \) is described by [10, eq. 3]:

\[ d\vec{\rho}_e(\ell) = I(\ell)\hat{n} d\ell \]  \hspace{1cm} (2)

and the general form of the coupled field on an arbitrary smooth convex shape is described by [10, eq. 6]:

\[ d\tilde{F}(Q | Q') = -\frac{jk}{4\pi} d\vec{\rho}_e(Q') \cdot \tilde{T}(Q | Q')G_o(kt)D \]  \hspace{1cm} (3)

where \( k \) is the wave number, \( \tilde{T} \) is the surface torsion factor, \( D \) is a surface constant, \( G_o \) is the propagation term, \( G_o(kt) = e^{-jkt}/t \), and \( t \) is the geodesic path length. The source is located at \( Q' \) and the victim monopole at \( Q \). The expressions simplify for a right circular cylinder (Fig. 2) with monopole antenna to [10, eq. 23]:

\[ d\tilde{E}_e(Q | Q') = C_o d\vec{\rho}_e(Q') \cdot \hat{n} \left[ V(\xi) - \frac{j}{kt} V(\xi) \left( \frac{j}{kt} \right)^2 U(\xi) \right] + T_o \frac{j}{kt} [U(\xi) - V(\xi)] G_o(kt)D \]  \hspace{1cm} (4)

where \( C_o \) is a constant from the canonical problem, \( T_o \) is a surface torsion constant based on launch angle and radius, and \( U(\xi), V(\xi) \) are the soft and hard Fock coupling functions, respectively. The Fock parameter \( \xi \) contains the geometric data along the geodesic and is described by [10, eqs. 25a, 25b, 27]:

\[ \xi = \frac{mt}{p_g} \]  \hspace{1cm} (5)

\[ m = \left( \frac{kp_e}{2} \right)^{1/3} \]  \hspace{1cm} (6)

\[ \rho_g = \frac{a}{\sin^3 \delta} \]  \hspace{1cm} (7)

where \( a \) is the cylinder radius and \( \delta \) is the geodesic launch-angle with respect to the cylinder axis.

Thus far, these equations are describing a single surface wave. If the problem formulation demands the inclusion of multiple surface waves, (2)–(8) must be repeated for each individual surface wave and its geodesic. The total coupled field at the victim antenna is the coherent sum of the coupled fields contributed by all surface waves. On a right circular cylinder geometry, the geodesic paths are helices and are transformed to straight line paths when the cylinder’s surface is unwrapped onto a plane, as shown in Fig. 3.

In the planar representation, the shortest geodesic path length is calculated by

\[ t = \sqrt{(a\Delta \phi)^2 + \Delta z^2} \]  \hspace{1cm} (8)

where \( \Delta \phi \) is the angular difference between the two antennas and \( \Delta z \) is their their axial offset. As a result, the surface wave coupling between two monopoles on a constant radius right circular cylinder is a function of angular difference and separation along the long axis of the cylinder.

CORRESPONDENCE 743
Fig. 3. Linear transformation of surface geodesic paths for right circular cylinder. Helical paths on cylinder surface become linear in planar representation.

Fig. 4. UTD contributors to radiation pattern of monopole on two-dimensional cylinder.

B. Antenna Pattern Calculations

UTD techniques can also be used to calculate radiation patterns from monopoles mounted on smooth-complex or simple two-dimensional cylindrical structures. The solution for a smooth cylinder geometry, at a minimum, should include the direct radiation contribution plus the two shortest surface waves launched into the far field added coherently, Fig. 4. With a two-dimensional right circular cylinder geometry, this pattern calculation is simple since surface parameters are constant along the geodesic path. If the surface is more complex yet still smooth, the pattern calculation is more complicated since variations in curvature along the geodesic must be considered. This is illustrated in Fig. 5, using a frequency and cylinder radius representative of the problem at hand. If the pattern from a right circular cylinder is an acceptable approximation (as examined in the next section) a large increase in efficiency may be realized by eliminating the need for multiple UTD radiation pattern computations from a complex surface during the optimization process.

III. METHODOLOGY

When optimizing over many variables, it is often acceptable to aggregate all considerations into a single objective function. This objective function produces a single value based on input from the problem variables and is a single measure of the “goodness” of any particular set of variables. Developing the problem in this framework makes it suitable for nearly any type of optimization technique, whether local or global. For this project, an aggregate objective function with variably weighted subelements is used. Discrete subelement weighting within the objective function is useful to the researcher if it becomes necessary to emphasize a particular variable or interaction within the problem domain.

A. Aggregate Cost Function

The aggregate objective function [11] is developed with vector notation simplifying presentation of the optimization methodology. Generally speaking, capturing all antenna-to-antenna interactions requires

\[ M = \binom{m}{2} = \frac{m!}{2(m-2)!} \]

coupling computations where \( m \) is the total number of antennas in the problem scenario. For this project, each coupling value is computed by including the two shortest helical surface waves added coherently at the coupled antenna location. As is common for GA optimization techniques, the raw coupled values (units of Volts) are linearly scaled and normalized, reducing the possibility of premature GA convergence.
due to a dominant variable magnitude in the objective function. For this implementation, the coupling values are linearly scaled to a reference coupling value from a selected baseline antenna configuration. The scaled coupled value is $c_i = \frac{E_i}{C_{\text{ref}}}$ and is further illustrated by Fig. 6.

In addition to the scaled antenna-to-antenna coupling values, measures of radiation pattern goodness for each antenna are included, as well as variance of the coupled fields. Including radiation pattern goodness requires $m$ additional elements in the cost vector. The variance of antenna-to-antenna coupling elements is included to achieve an optimum yet balanced solution avoiding a skewed coupling distribution (i.e., one antenna pair having a much greater coupling value than the rest of the antenna pairs). Radiation pattern and variance elements are also linearly scaled to a reference value in the same manner as the coupled field. Combining, the total number of elements in the objective vector is $M + m + 1$:

$$C = [c_1, c_2, \ldots, c_M, c_{\text{var}}, c_{p_1}, \ldots, c_{p_m}]$$ (9)

where $c_i$ is the scaled E-field coupling value of the $i$th antenna pair, $c_{\text{var}}$ is the scaled variance of all coupling values, and $c_{p_i}$ is the scaled pattern value of the $i$th antenna. Finally, the complete aggregate fitness function to be minimized is written:

$$\text{Fitness} = \log_{10} \left( \frac{C \cdot W^T}{M + m + 1} \right)$$ (10)

where $W^T$ is the transpose of the weighting vector of length $M + m + 1$. The weighting vector provides a feature to emphasize or deemphasize any element of the cost vector to better meet design requirements. In this construct, the fitness function is to be minimized to find the optimal solution.

B. Antenna Radiation Pattern Analysis

In order to optimize for the roll-axis antenna radiation pattern, the coverage requirements for each radiator must be stated. For this project, the pattern requirements were simplified to two categories, one for an upper fuselage radiator and one for a lower fuselage radiator. The coverage requirements selected are based on an assumed maximum roll angle of $30^\circ$ for a large aircraft and are graphically shown in Fig. 7. Using these general coverage requirements, the “goodness” of the roll-axis pattern can be determined by a sum-of-squares calculation of the deviation of the calculated antenna pattern versus the pattern coverage requirements.

This simplified approach assumes that the radiation pattern from a monopole on a two-dimensional cylinder adequately approximates the pattern of the same antenna on a more complex air vehicle. To
determine the validity of this approximation, multiple measurements were made in a compact antenna range on a 1/100 scale model Boeing 747-200 aircraft, Fig. 8. Relative radiation pattern measurements are compared with the cylinder radiation patterns in Fig. 9 at the angles the monopoles were mounted on the model. Relative radiation pattern measurements show good agreement with a simple two-dimensional cylinder pattern at VHF frequencies, although the measurements show the effects of the wings on the radiation pattern which is not modeled in the UTD analysis. The right circular cylinder approximation is therefore used for all radiation pattern analysis for optimization runs on the complex Boeing 747-200 surface model, Fig. 1, at a large savings in computational cost.

IV. PROBLEM SCENARIOS

We consider problem scenarios of one, three, and eight movable antennas. The simple two-dimensional (i.e., one movable antenna) case, where results could
be exhaustively validated, gave confidence in the methodology, optimization techniques, and computer coding. The two-dimensional optimization included seven fixed radiators and an optimum position for an additional radiator was found. The final scenario addressed was an optimization of three movable antennas which was performed on both the cylinder model and a complex Boeing 747-200 model where direct performance comparisons could be made.

A. Single Movable Antenna—Right Circular Cylinder Model

Each antenna position on a simple right circular cylinder model is completely described by two variables: offset angle from vertical and distance along the cylinder from a reference location. Therefore, an optimization with a single antenna is that of only two independent variables. If fixed antennas are included in the problem scenario, their coupling effects are captured by the aggregate function of (10) but do not add to the dimensions of the design space. Table I shows the baseline and reference configuration.

Using these antenna positions and the fitness function of (10), the position of antenna 1 was varied subject to the constraints $6 \leq z \leq 56$ m and $|\phi| < 90^\circ$; the resulting fitness values over the design space are shown in Fig. 10. The constraints correspond to the entire upper fuselage from above the cockpit to the base of the vertical stabilizer on the Boeing 747-200.

The global optimum location in this design problem, found by exhaustive search, is $(z, \phi) \approx (56, -10^\circ)$. Note the presence of a strong local minimum at approximately $(56, +10^\circ)$ as well as many local minima throughout the design space. The multiple local minima are potential gradient traps for local search techniques and the strong local minimum may be difficult for the GA to avoid since half of its genetic coding is identical to the true global minimum.

Due to the computational simplicity of the two-variable problem combined with the right circular cylinder model, many GA parameterizations and techniques could be explored and compared. Generally speaking, all simple GA techniques with various parameterizations converged to either

<table>
<thead>
<tr>
<th>Antenna Number</th>
<th>Radiation Pattern (Upper/Lower)</th>
<th>z (meters)</th>
<th>$\phi$ (degrees)</th>
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<tr>
<td>1</td>
<td>Upper</td>
<td>17.75</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Upper</td>
<td>27.00</td>
<td>0</td>
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<tr>
<td>3</td>
<td>Upper</td>
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<tr>
<td>4</td>
<td>Upper</td>
<td>41.00</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Lower</td>
<td>40.00</td>
<td>180</td>
</tr>
<tr>
<td>6</td>
<td>Lower</td>
<td>33.00</td>
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<td>Lower</td>
<td>28.50</td>
<td>180</td>
</tr>
<tr>
<td>8</td>
<td>Lower</td>
<td>13.50</td>
<td>180</td>
</tr>
</tbody>
</table>

Note: $z$ is distance along fuselage axis, $\phi$ is angle from vertical (positive for port, negative for starboard).
Fig. 11. Convergence characteristics of select examples of two-dimensional GA optimizations. Data are average of 100 independent runs.

Fig. 12. Convergence location of 100 independent Micro-GA runs on two-variable problem domain. Note large dispersion of converged solutions for each run. In contrast, simple-GA techniques fell within 1 or 2 resolution cells for each optimization run.

By visual analysis of Fig. 11, the convergence characteristics of the micro-GA [12] appear least desirable. Despite this appearance, closer considerations of the number of UTD computations required to reach convergence (Table II), the efficiency of the micro-GA technique is apparent. In this case study, this computational advantage has the drawback of greater dispersion of the final converged solutions and larger average error from the true global minimum. The dispersion of the final optimized locations for the 100 micro-GA runs is shown in Fig. 12.

This process was demonstrated with the cylinder model in eight (four movable antennas) and sixteen variables (eight movable antennas) with qualitatively similar results. With this completed, confidence in the aggregate function, UTD computational code, and binary GA algorithms\(^2\) was gained. As one may expect, adding additional movable antennas to the scenario resulted in progressively better optimized performance. Finally, a more detailed comparison between optimizations on the cylinder versus a lofted Boeing 747-200 aircraft model was completed with three movable antennas (six variables).

### Bivariate GA Convergence to Best Solution, Average Generation of Convergence

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>20</td>
<td>71.66th</td>
<td>8,640</td>
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<td>30</td>
<td>43.26th</td>
<td>7,920</td>
</tr>
<tr>
<td>40</td>
<td>47.19th</td>
<td>11,520</td>
</tr>
<tr>
<td>50</td>
<td>43.57th</td>
<td>13,200</td>
</tr>
<tr>
<td>5</td>
<td>81.00st</td>
<td>2,430</td>
</tr>
</tbody>
</table>

Note: Population size shown in first column, average generation at which convergence was achieved shown in second column, total number of cost function evaluations needed for convergence shown in third column.

As the number of variables increased, computational time became prohibitive for research purposes, even with the simple right circular cylinder model and UTD techniques. An increase in efficiency of the GA implementation was necessary to make the approach practical. In order to gain additional efficiency, an initial population seeding simple-GA technique was explored.

In this problem scenario, the design space was limited to the highlighted region in Fig. 1 ranging from 44–50 m along the aircraft fuselage. This size region was selected due to the limits of computer resources to implement a first principle method-of-moments (MoM) computation and the quality of the surface model at that location.

Two upper fuselage antennas and one lower fuselage antenna were included in the optimization and initial coupling values were based on logical (but arbitrary) starting positions. The optimizations included unity weighting factors and implemented the same radiation pattern and variance terms in

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\(^2\)GAFortran V1.7a by David L. Carroll, CU Aerospace, 2004 South Wright Street Extended, Urbana, IL 61802, (carroll@cuaerospace.com), +1-217-333-8274.
Fig. 13. Comparison of GA and Nelder-Mead local search performance. Note that magnitude of fitness function is relative to starting reference values and not necessarily comparable. Trends and relative performance between techniques is comparable.

TABLE III
Final Optimized Antenna Locations and their Associated Fitness Values
Comparison of Cylinder and Lofted Model Optimization

<table>
<thead>
<tr>
<th>Initial Reference</th>
<th>Cylinder</th>
<th>747-200 Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator</td>
<td>Position</td>
<td>Fitness</td>
</tr>
<tr>
<td>1</td>
<td>+10.0°, 44 m</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>−10.0°, 50 m</td>
<td>−0.1559</td>
</tr>
<tr>
<td>3</td>
<td>+180°, 46 m</td>
<td>−0.1613</td>
</tr>
<tr>
<td></td>
<td>+0.1°, 44 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>−0.1°, 50 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+10.5°, 50 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+172°, 47.6 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>−178°, 47 m</td>
<td></td>
</tr>
</tbody>
</table>

Note: Positive angles are toward port, negative angles are toward starboard.

the objective function as discussed previously. Optimizations were initially completed with random initial populations then seeded with a population

Fig. 14. MoM surface currents in $\log_{10}$ color scale. Forward upper antenna is source, aft victim antenna in view. MoM coupling predictions were similar to UTD coupled E-fields.
randomly distributed around a two antenna minimum coupling arrangement derived mathematically for a right circular cylinder model. In addition, the Nelder-Mead [13] local search was implemented at the end of each generation using the best GA value as the starting point. (This highlighted how a GA could be augmented with a simple hybrid technique and was not intended to be an efficient implementation of such concepts. Fig. 13 shows a comparison of all techniques used for the three antenna, right circular cylinder-model optimization. Of note is the performance gain from seeding the population based on a two antenna scenario versus using an initial random population.

When applying these algorithms to a realistic surface model computational time on a Silicon Graphics 400 MHz system allowed for only one computational run of each type. For direct comparison between the cylinder model and the complex lofted model, identical parameterizations and identical initial seed populations were used. As shown in Fig. 13, the relative performance of each technique on the complex lofted model was qualitatively similar to that of the simple cylinder model. In addition, the final antenna positions of Table III are similarly comparable. (In Table III, antenna position is expressed in normalized parameters. The parameter $z$ is the station-line coordinate in meters measured from the aircraft nose and the parameter $\phi$ defines the angle from top of the fuselage, with positive angles toward port, negative angles toward starboard.)

As a check and possible validation of the UTD approximations and optimized results, surface current MoM computations [14] were used to calculate all coupling interactions for the start configuration and the final optimized positions. Based on computer resource limitations, the meshed area slightly exceeded the three antenna design space and a more desirable termination of the model’s edges could not be included. Graphical output of the MoM surface currents in the optimized are shown in Fig. 14 (the edge effects are clearly seen in the complex surface current pattern). Generally speaking, the MoM coupled power solutions changed proportionally to the UTD coupled E-fields between the initial starting location and final, optimized antenna positions. This was not a full validation of the UTD solutions and the optimized locations, but supported the validity of the UTD based approach on this type of geometry and problem domain.

V. CONCLUSION

A general methodology was formulated to optimize positioning for any number of radiators on an aircraft surface. The optimization could include any number and combination of movable and stationary radiators and, with its aggregate objective function framework, is only limited by the computational time and resources. The general methodology and UTD assumptions were supported by compact antenna range measurement on a scale model and with a first-principle MoM technique.

Finally, many GA parameterizations and techniques were used to optimize on simple and complex models. During trials using a simple right circular cylinder model, the micro-GA showed superior efficiency to converge toward a solution, but suffered from greater positioning error versus the known optimal solutions. When applying these techniques to a more complex scenario and detailed surface model, computational time increased drastically. To gain back some optimization efficiency, a novel population seeded simple-GA technique was successfully implemented and compared with other approaches.

References


I. INTRODUCTION

Binary integration was conceived by Schwartz [1] as a simplified detector implementation that has nearly optimum performance when its parameters are properly chosen. If in a batch of $N$ single pulse responses, $M$ or more detections are observed, then an overall detection is declared. A method for calculating the relevant detection probabilities was provided in an earlier paper [2] that expanded on results provided by Weiner [3]. Cascaded detection schemes that have two main noncoherent detection stages have been proposed to handle both detection and range/Doppler resolution issues simultaneously. The two stages, the first, binary integration, followed by the second, standard noncoherent integration, have been proposed as one type of a cascaded detection scheme. The type of cascaded detection of interest here reverses this order, so that the first stage is noncoherent integration and the second is the binary integration. With this latter cascaded detection, $M$ or more required detections are made on the basis of $N_f$ noncoherently integrated pulses instead of single pulses. Much of the required background has already been developed in [2], and we highlight here those modifications required to extend the results of [2] to the above cascaded detection problem.

II. THE STANDARD BINARY INTEGRATION CASE,

$N_f = 1$

References [2], [3], and [5] considered all four of the Swerling fluctuation models (respectively, SW-I, SW-II, SW-III, and SW-IV). To extend those results to cascaded detection, we first outline results for the standard, noncascaded, binary integration ($N_f = 1$) and then show how these results are easily extended for the general $N_f$. Expressions for the probabilities of detection for all four Swerling fluctuation models are presented.

For a constant target model with detection probability $p$, the $(N,M)$ binary integration probability of detection is given by the cumulative binomial distribution function,

$$C(N,M,p) = \sum_{m=M}^{N} \frac{N!}{m!(N-m)!} p^m (1-p)^{N-m}$$

(1)

where $p$ is the single pulse detection probability $p(t,y)$, and where

$$p(t,y) = \int_{y}^{\infty} e^{-(y+t)} I_0 (2\sqrt{\sigma}) dv$$

(2)

with $t$ the target signal-to-noise ratio (SNR), and $y$ the normalized threshold level [5].

When the target fluctuates, we need to weight the detection probability, as given by (1), by the joint SNR target fluctuation density and integrate over all

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References:

Geometrical theory of diffraction.

Ray analysis of mutual coupling between antennas on a convex surface.

Evolutionary Algorithms for Solving Multi-Objective Problems.

Micro-genetic algorithms for stationary and non-stationary function optimization.

A simplex method for function minimization.

EIGER: electromagnetic interactions generalized.