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IVIF-Based Hybrid-Weighted Model for Seeker's Multi-Port Damage Assessment Under HPM

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Abstract

In existing research on non-contact damage by high-power microwave (HPM) systems to electronic systems such as seekers, challenges include high risk, high cost, and a scarcity of HPM-specific damage assessment models. To address this, this paper proposes a multi-port HPM damage level assessment model based on interval-valued intuitionistic fuzzy (IVIF) sets. Firstly, electromagnetic modeling and field-circuit coupling simulation of multi-target structures provide input data from field-circuit simulations. Secondly, a multi-indicator fuzzy matrix reflecting system damage uncertainty is formed using interval fuzzy membership functions. Thirdly, an information entropy-driven dynamic weighting mechanism weights each indicator's fuzzy distribution characteristics, and hybrid weights are constructed by dynamic and fixed weights to optimize parameter range rationality. Finally, using hybrid weights and the exponential damage mapping function, we achieve probabilistic fusion of multiple parameters and determine damage levels from the probability results. Assessment shows that under the same incident field strength of 25 kV/m, electromagnetic simulation software-based simulation assigns a composite damage probability of 0.85 to L-band Port 5 and 0.096 to X-band Port 6, highlighting the contrast between the dominant L-band hotspot (Port 5) and the low X-band response at Port 6 under identical irradiation.

Keywords: damage assessment under high power microwave (HPM); field-circuit coupling simulation; fuzzy matrix; multi-port seeker; interval-valued intuitionistic fuzzy (IVIF) set



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1. Introduction

In modern warfare, the proportion of non-contact strike models continues to rise. Especially in the field of precision-guided munitions, electromagnetic means have become an important supplement for efficiently countering key electronic systems. As a typical new-type combat capability, the high-power microwave (HPM) system has the ability to release high-energy electromagnetic pulses in a short time and can cause non-kinetic damage to electronic targets [1]. The current mainstream precision-guided munition systems, including various missile-borne seekers with terminal guidance capabilities, have key internal components such as low-noise amplifiers (LNAs), control chips, and pyrotechnic fuzes, and these systems have extremely high electromagnetic sensitivity [2–4]. Although the seeker system has excellent performance, it is also vulnerable to interference from in-band HPM signals, resulting in breakdown or overload damage, and faces similar non-contact damage risks [5].

The traditional damage assessment models rely on live fire tests and empirical thresholds. However, in the context of highly integrated modern electronic systems, the LNA and the detonation circuit in the seeker are often packaged in a millimeter-scale space, with limited measurement channels, poor controllability of experiments, and high security risks brought by HPM attacks, which significantly increase the difficulty of actual measurement [6,7]. Therefore, researchers have gradually shifted to models based on numerical simulation and modeling. By constructing three-dimensional model, device models, and combining uncertainty quantification techniques, a digital assessment linking simulation parameters to damage probability is achieved, enhancing the intelligence and refinement of the judgment, and complementing targeted physical experiments [8].

Cheng et al. [9] tested failure thresholds of electronic devices under HPM damage effects, including transistors, TTL circuits, and CMOS components. The study revealed the sensitive terminals of different devices along with their failure mechanisms, thereby establishing crucial foundations for threshold determination. Based on similar experience, studies on HPM systems damage assessment have built multi-dimensional assessment systems. Chen et al. [10] set up small-scale HPM radiation environments, took planar spiral antennas as research objects, and used least-squares fitting to establish linear relationships between HPM radiation field strength and antenna coupling voltage. This process verifies the model accuracy, which is crucial for evaluating device sensitivity to HPM radiation. Liu et al. [11] selected assessment indicators from four aspects, including microwave, radiation, drone swarm, and electronic systems. They combined the expert scoring model with the entropy weight model to create a damage assessment model. This model effectively provided guidance for the assessment of seeker systems. In a multi-indicator assessment, abnormal parameters have a limited impact on results. To address this, Qian et al. [12] combined the entropy weight model with variable weight theory to build variable weight vectors, which were used to correct abnormal indicators. This corrected approach was then combined with fuzzy comprehensive assessment to achieve the health assessment of drones, thereby providing ideas for the application of dynamic weight mechanisms.

Compared with fixed threshold pass/fail rules and single-valued fuzzy comprehensive evaluation, IVIF intervals retain hesitation when HPM coupling indicators are noisy [13–16]. Notably, the uncertainty in HPM damage assessment is not only derived from measurement limitations but also from the fuzziness of assessment criteria and the ambiguity of parameter correlations. Interval-valued intuitionistic fuzzy (IVIF) sets, as an effective tool for handling uncertain and fuzzy information, have shown unique advantages in characterizing such complex uncertainties [13,14]. By simultaneously considering membership degree, non-membership degree, and hesitation degree in the form of intervals, IVIF sets can more comprehensively describe the ambiguity and uncertainty in multi-parameter assessment that are difficult to quantify accurately [15,16].

The dynamic weighting models are capable of autonomously adjusting the importance assigned to various features based on operational conditions and simulation data, enhancing the adaptability of the assessment [17]. The model integrates real-time simulation outputs with historical knowledge, enabling dynamic weight adjustment through feature extraction and influence analysis [18].

Related Work and Methodological Positioning

Prior HPM damage studies emphasized device failure thresholds, coupling path measurement, and multi-indicator scoring under radiation or swarm scenarios [9–12]. Threshold-based routes map electrical exceedance to pass/fail damage calls [9]; fuzzy comprehensive and entropy weight routes aggregate multiple indicators into composite scores for equipment or platform health assessment [11,12]. IVIF and related interval fuzzy

models extend single-valued scores to membership–non-membership intervals for multi-criteria decisions under criterion ambiguity [13–16]. Dynamic and hybrid weighting further adjusts indicator importance when indicator distributions shift across scenarios [17,18].

Table 1 summarizes how the present IVIF hybrid assessment route relates to these literature families. The proposed framework targets multi-port seeker assessment under identical field–circuit simulation inputs: it retains IVIF intervals and hybrid entropy-fixed weights, then maps composite probabilities to discrete Levels I–IV for port prioritization rather than claiming standalone physical burnout certification. Relative to threshold-only HPM device studies [9] and platform-level entropy scoring [11,12], the present route differs by retaining IVIF interval hesitation, hybrid entropy-fixed weights, and eight port field–circuit metrics within one repeatable pipeline. Compared with recent LNA HPM damage reports [3–5] and UAV or swarm scoring routes [6,7], the contribution is port-level prioritization under identical simulation inputs, with Section 3.3 ablations testing whether interval fuzziness and hybrid weighting are non-redundant rather than optional extensions of fixed threshold rules.

Table 1. Literature assessment routes versus the proposed IVIF–hybrid framework.

Route	Representative Use	Uncertainty	Weighting	Output
Fixed threshold [9]	HPM device terminals	Pass/fail	None	Binary exceedance
Fuzzy comprehensive [12]	Platform health	Single-valued μ	Variable/entropy	Composite score
Entropy scoring [11]	Multi-indicator systems	Crisp indicators	Entropy	Weighted score
IVIF MCDM [13–16]	Multi-criteria decisions	Interval μ, ν	Operator-based	Rank/score
Proposed IVIF–hybrid	Multi-port seeker ports	IVIF intervals	Hybrid entropy + fixed	Port P + Levels I–IV

Building upon this background, this study focuses on representative high-risk components such as guidance systems. Under L-band and X-band frequencies, this study establishes a damage assessment model based on IVIF sets combined with a dynamic weighting mechanism, offering a solid foundation for assessing the effectiveness of and supporting mission planning for HPM systems [19]. The assessment model quantifies multi-parameter uncertainties and supports risk-informed damage decisions. The assessment objective is as follows: the model outputs port-level composite damage probability and Levels I–IV as decision-support risk indicators from simulated electrical indicators and IVIF aggregation; it does not alone certify physical burnout without further validation. In the study, three contributions are made and listed below:

- IVIF sets are utilized in this paper to represent port electrical parameters, quantifying fuzziness from measurement errors and damage thresholds by constructing a fuzzy matrix that contains membership and non-membership degrees, thereby overcoming the uncertainty challenges inherent in traditional fixed threshold methods.
- Developing a hybrid mechanism integrating entropy-driven dynamic weighting and fixed weighting. The approach dynamically adjusts parameter importance by combining data-driven insights from fuzzy matrix entropy with fixed weights through adaptive weighting.
- Establishing a probabilistic fusion that synergistically aggregates multi-parameter uncertainties through hybrid-weighted integration and maps comprehensive probabilities to discrete damage levels via a threshold-based classification system.

Figure 1 links electromagnetic simulation software port waveforms, IVIF matrices, hybrid weights, and port-level composite probabilities to discrete Levels I–IV for eight observation ports under HPM irradiation.

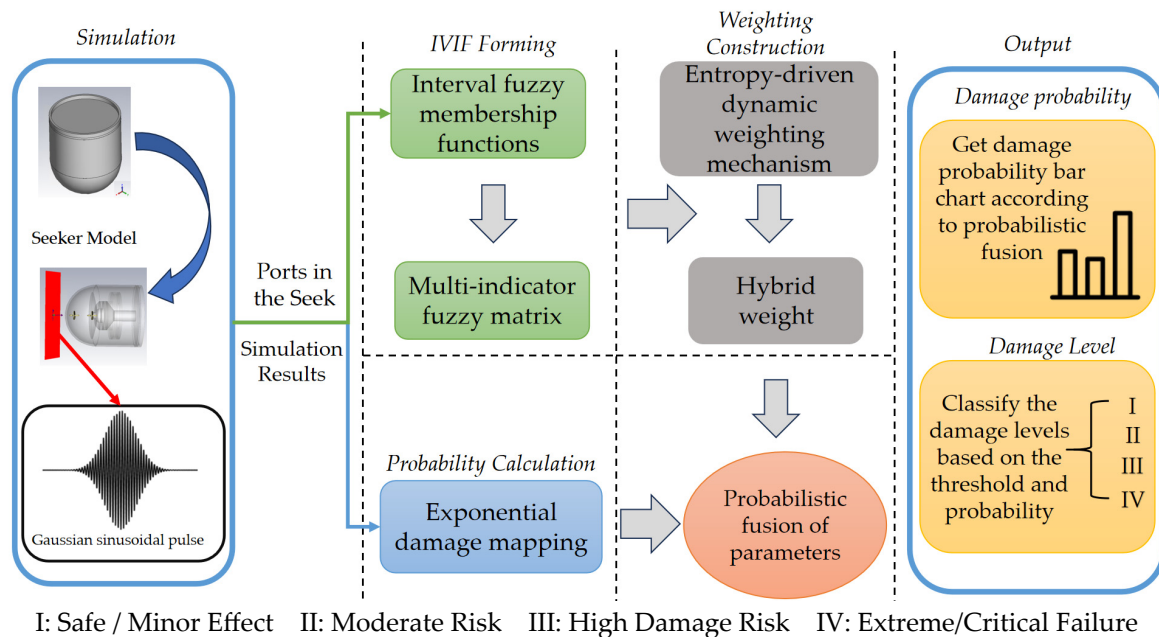


Figure 1. Diagram of seeker's multi-port damage assessment under HPM.

The subsequent sections of this paper are organized as follows. Section 2 formulates the IVIF-based damage assessment framework and its theoretical foundation. Finally, Section 3 compares the proposed assessment rule with literature-based alternatives (B1–B4) and reports parameter sensitivity; Section 4 concludes key findings and study scope.

2. Damage Assessment Model Based on Fuzzy Intervals and Hybrid Weights

This section introduces the interval fuzzy hybrid probability fusion assessment model for seeker ports in complex electromagnetic environments. The model uses port response data from front-end simulations as input. It generates damage level decisions through a three-stage assessment chain: fuzzy representation, hybrid weighting, and probability fusion. This forms a complete assessment framework. The model effectively handles electromagnetic damage assessment for seeker systems.

2.1. Assessment Framework

The assessment from simulation to damage level output can be divided into the following stages: simulation data extraction, fuzzy modeling and weight generation, probability fusion, and level classification. Each link is interconnected, forming a logical, closed-loop damage assessment chain. The flowchart is shown in Figure 2.

The assessment uses the electromagnetic field and circuit simulation results as the data. Field simulation, by constructing a target geometric model and setting the parameters of the radiation source, outputs the distribution results of the irradiation field at a specific frequency band. The circuit simulation extracts the response voltage and current time series of each port under external field excitation, providing raw data for the calculation of damage parameters.

For the extracted raw data, the system performs fuzzy modeling. Based on the proportion of each indicator exceeding the safety threshold, corresponding interval-valued intuitionistic fuzzy numbers (IVIFNs) are constructed, including membership and non-

membership degree intervals, to express the fuzzy cognitive structure of the parameters' support for and opposition to the damaged target. After completing the fuzzy expression, the system further calculates the hybrid weight of each parameter, which integrates the dynamic weight and fixed weight. The information entropy for the dynamic weight is derived based on the interval width and conflict degree, and the parameter weight vector is generated through normalization.

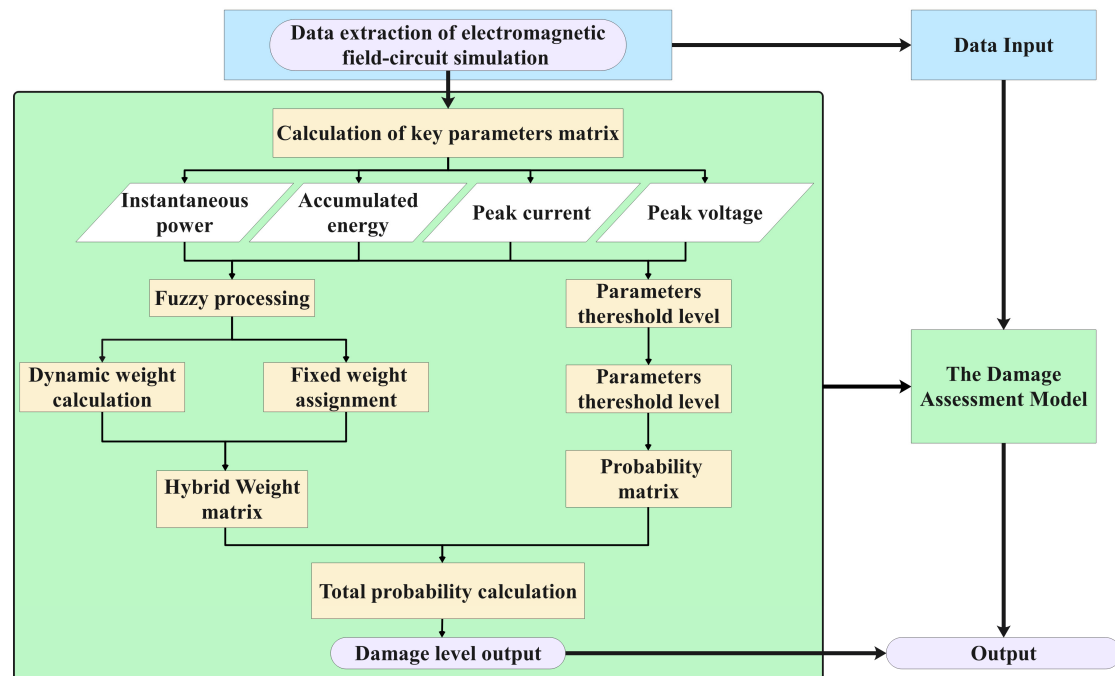


Figure 2. Damage assessment flowchart.

Finally, the system enters the stage of assessing the probability of damage. For each type of electrical parameter, its damage probability is calculated, and the exponential response function is used to perform nonlinear mapping of the relationship between parameter values and thresholds. Subsequently, based on the generated hybrid weight vector, the weighted fusion of each damage probability is carried out to calculate the comprehensive probability. According to operational risk-band thresholds [0.3, 0.6, 0.9] used for preliminary four-level partitioning (robustness is examined in Section 3.4 sensitivity analysis), the total probability is mapped to the corresponding damage levels (Levels I to IV), and finally, the level labels and results of each port are output for subsequent situation analysis and decision making.

2.2. Simulation Objects

In the simulation, the seeker is selected as the simulation object, and a corresponding model is established in CST Studio Suite 2022. Meanwhile, partial ports of the low-noise amplifier and explosive control board inside the seeker are chosen as observation ports. To obtain authentic and accurate simulation results, the modeling process must consider the electrical conductivity of metal materials and the electromagnetic parameters of different dielectric materials. In terms of simulation, this study adopts Gaussian sinusoidal pulses as the simulation waveform and conducts simulations within the frequency bands commonly used by high-power microwave systems, specifically selecting the L-band and X-band for analysis. For excitation, plane waves are used to simulate intense electromagnetic pulses irradiating the target. The center frequencies of the selected L-band and X-band are 1.2 GHz and 10.3 GHz, respectively, with a pulse width of approximately 40 ns for both bands. The

initial electric field intensity is set to 25 kV/m, and the spatial distance is configured as “open” to represent irradiation by intense electromagnetic pulses in an infinite space, where 25 kV/m simulates the electric field intensity at the target. The excitation direction is set to frontal irradiation of the target. The plane wave irradiation direction of the seeker is aligned with the front of the seeker, as summarized in Figure 3.

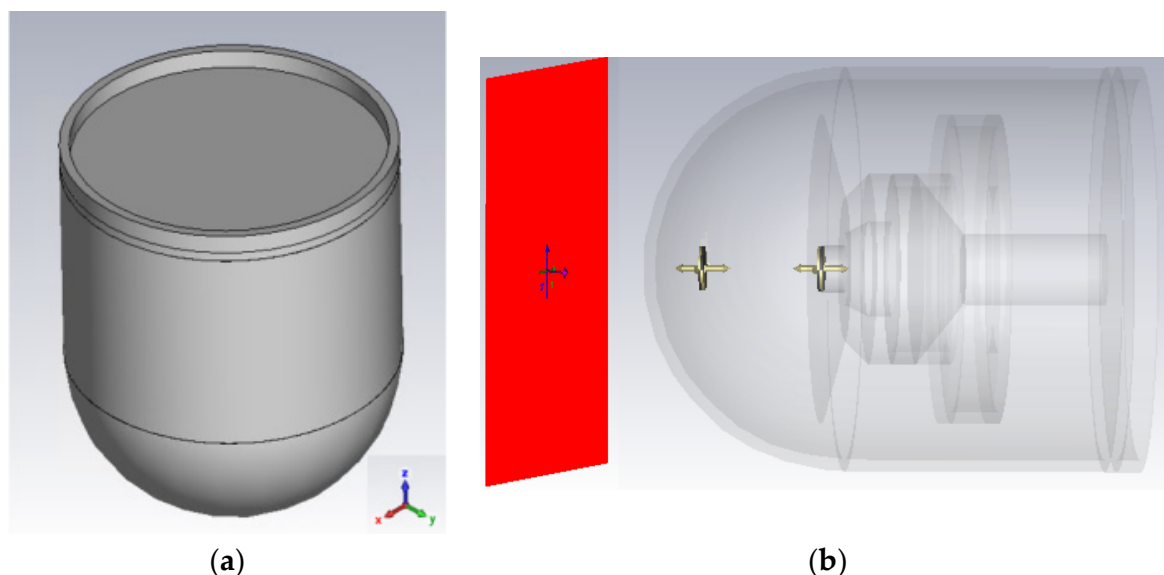


Figure 3. Seeker simulation model (schematic). (a) Seeker layout. (b) Plane-wave incidence. Layout is illustrative; mesh refinement follows the CST adaptive scheme described in Section 2.2.

The selection of ports mainly focuses on two PCBs inside the seeker model: the explosion control board (decoder IC SC2272-T4) and the low-noise amplifier front-end. Seven ports monitor representative nets on the explosion control chip; Port 8 is the LNA RF input (approximately 2.1 GHz in band, with L- and X-band HPM treated as out-of-band coupling). Their electrical roles are summarized in Table 2.

Table 2. Port information and corresponding port numbers.

Port Number	Port Information	Port Number	Port Information
1	Address/data, explosion control IC	5	Data input, explosion control IC
2	Address/data, explosion control IC	6	Oscillator net, explosion control IC
3	Address/data, explosion control IC	7	Oscillator net, explosion control IC
4	Address/data, explosion control IC	8	LNA RF input (~2.1 GHz)

Field-circuit coupling simulations in CST Studio Suite 2022 provide the port voltage and current waveforms used as assessment inputs under the excitation settings stated above. The simulation outputs time-domain distribution data of voltage and current at key internal positions of the target. By analyzing these time-domain waveforms, ports with significant coupling responses inside the target are identified, providing basic data support for subsequent circuit-level modeling and damage assessment.

The field-circuit model is implemented in CST Studio Suite 2022 using the time-domain transient solver with hybrid electromagnetic–circuit co-simulation. At a high level, the seeker enclosure is represented as a metallic cavity with dielectric inserts housing two PCB

assemblies, namely the explosion control decoder SC2272-T4 and the LNA front-end; frontal plane-wave incidence aligns with the seeker optical axis as shown in Figure 3. Material assignments use copper conductors and FR4-grade dielectric defaults associated with the monitored nets; exact stack-ups follow the configuration-sensitive CAD retained offline. Open boundary conditions simulate irradiation in unbounded space at 25 kV/m. The time step is set automatically according to the solver stability criteria for the 40 ns Gaussian pulse. Global hexahedral meshing uses fifteen cells per wavelength near and far from the model and twenty cells along the maximum near-field box edge. Refinement is checked by reducing the discretization until the Port 5 monitor voltage changes by less than 2% between successive levels. Representative seeker envelope dimensions are approximately 150–175 mm in extent with a maximum outer diameter near 120 mm in the archived CST assembly; detailed aperture glazing and internal stack-ups remain configuration-sensitive and are not disclosed. Archived port waveforms and the assessment scripts support recomputation of the subsequent risk assessment tables under the stated thresholds.

2.3. Damage Assessment Model

To quantitatively evaluate the damage level, a multi-attribute assessment model based on IVIF theory [20] and hybrid weighting is constructed. This model defines an assessment attribute set corresponding to key indicators. The fuzzy attribute mapping module addresses assessment uncertainty by converting each attribute's score into an IVIFN. In IVIFN construction, the membership interval is established based on a specific function, while the basic membership degree calculation adopts a piecewise functional form [21]. This piecewise function determines membership value rules across different intervals by comparing the variable x with key thresholds, with its mathematical expression in (1):

The assessment attribute set comprises four port metrics derived from the CST waveforms: peak instantaneous power, pulse energy, peak current, and peak voltage. Although peak power is algebraically related to voltage and current at an instant, the four quantities are not used as redundant copies of one signal: energy integrates the coupled waveform over the 40 ns pulse and therefore captures duration effects that peaks alone omit, while voltage and current peaks can diverge when port impedance differs across nets. Each metric is mapped to its own IVIF membership interval and partial damage probability before hybrid-weighted fusion, and entropy-driven dynamic weights down-weight indicators whose interval widths collapse across ports, mitigating double-counting of the same electrical excursion [9–11].

$$\mu(x) = \begin{cases} 0, & x \leq a \\ \frac{b-a}{c-a} \cdot \frac{x-a}{b-a}, & a < x \leq b \\ \frac{b-a}{c-a} + \frac{c-b}{c-a} \cdot \frac{x-b}{c-b}, & b < x \leq c \\ 1, & x > c \end{cases} \quad (1)$$

where a , b , and c are sorted thresholds denoting the lower safety bound, the upper warning bound, and the upper danger bound, respectively ($a < b < c$). The crisp membership $\mu(x)$ is defined as a continuous piecewise linear function that increases with the observed parameter x across the safety, warning, and danger regions: $\mu(x) = 0$ for $x \leq a$; $\mu(x)$ rises linearly from 0 to $(b - a)/(c - a)$ for $a < x \leq b$; continues linearly from $(b - a)/(c - a)$ to 1 for $b < x \leq c$; and remains at 1 for $x > c$, as given in Equation (1). This definition satisfies $\mu(a+) = 0$, $\mu(b) = (b - a)/(c - a)$, $\mu(c) = 1$, and is monotone and continuous at $x = b$ and $x = c$, thereby avoiding abrupt jumps at the warning and danger limits. It provides a clear, trend-driven basis for converting each electrical parameter into a deterministic membership degree before constructing the IVIF interval in Equations (2)–(4) [22].

Traditional models usually directly compare simulation data with fixed thresholds, but they ignore the sources of uncertainty. The fuzzy boundary of the damage state is jointly described by the membership intervals $[\mu_L, \mu_U]$ and non-membership intervals $[\nu_L, \nu_U]$ of the theory. For each electrical parameter x , the crisp membership $\mu(x)$ is obtained from Equation (1); interval IVIFNs are built from $\mu(x)$, not by intervalizing raw x . Membership bounds are defined in (2):

$$[\mu_L, \mu_U] = [x - \Delta x, x + \Delta x], \quad (2)$$

where $\mu_L = \max(0, \mu(x) - \delta(x))$, $\mu_U = \min(1, \mu(x) + \delta(x))$, and ν bounds use the same half-width $\delta(x)$ from Equation (3). We extend the deterministic μ into a membership interval $[\mu_L, \mu_U]$ by introducing a dynamic width function. This expansion transforms the crisp single-value membership into a fuzzy interval, capturing both the core trend and the inherent uncertainties. The dynamic width is designed with a Gaussian decay function centered at b to adapt to the membership degree's distribution:

$$width(x) = \alpha + \beta \cdot \exp\left(-\left(\frac{x - b}{c - a}\right)^2\right), \quad (3)$$

where α is defined as a fundamental width constant with a value of 0.05 and quantifies the intrinsic baseline uncertainty inherently present in the system. β , functioning as an amplitude modulation coefficient set to 0.15, governs the peak uncertainty within the critical transition zone [23]. As the measured value approaches threshold b , the exponential property of the Gaussian function activates a maximum interval width of 0.20.

$$\begin{cases} \mu_L = \max(0, \mu(x) - width(x)) \\ \mu_U = \min(1, \mu(x) + width(x)) \end{cases} \quad (4)$$

By ensuring that $\mu_L \leq \mu_U$, $\nu_L \leq \nu_U$, and that all values are within the $[0, 1]$ interval, the internal definitions strictly meet the core constraint condition of $\mu_U + \nu_U \leq 1$. After these steps, the function outputs an IVIFN composed of the membership interval and non-membership interval, thereby completely achieving the quantitative expression of fuzzy information.

The CST port waveforms are deterministic simulation outputs. The IVIF intervals in Equations (2)–(4) therefore encode epistemic uncertainty in threshold exceedance and damage criteria interpretation rather than stochastic measurement noise in the waveforms themselves.

After obtaining the IVIF membership information for different electrical parameters of each port, further comprehensive processing of the fuzzy information is required to infer the degree of port damage. To describe the fuzziness of each attribute and construct dynamic weights accordingly, this paper introduces the following entropy-based uncertainty measurement function, shown in (5)

$$h_j = \frac{2 - |\mu_L - \mu_U| - |\nu_L - \nu_U| + \pi_L + \pi_U}{2 + |\mu_L - \mu_U| + |\nu_L - \nu_U| + \pi_L + \pi_U}, \quad (5)$$

where μ_L and μ_U are the lower and upper bounds of the membership degree of the attribute, and ν_L and ν_U are the lower and upper bounds of the non-membership degree. The upper and lower bounds of the confidence interval are respectively defined as (6)

$$\pi_L = 1 - \mu_U - \nu_U, \quad \pi_U = 1 - \mu_L - \nu_L, \quad (6)$$

Based on the above uncertainty metric, the weights are generated using the following normalization Formula (7)

$$\omega_j^{\text{dynamic}} = \frac{1 - h_j}{\sum_{k=1}^n (1 - h_k)}, \quad (7)$$

where h_j also represents the uncertainty; the lower the uncertainty, the higher the dynamic weight, reflecting the stable contribution of the parameter to damage assessment. Normalization ensures that the sum of weights is 1, meeting the requirement of weighted summation [24].

Fixed weights reflect the prior physical importance of parameters and are directly set using recommended values from the literature, standards, or expert experience. They are defined by the following array:

$$\omega_j^{\text{fixed}} = \omega_{\text{fixed}}(j), \quad (8)$$

If a parameter has a significant impact on damage, $\omega_{\text{fixed}}(j)$ can be manually increased. Set fixed weights are equal to ensure the anchoring of the prior mechanism of cognition. To balance the data-driven characteristics of dynamic weights and the mechanism cognition characteristics of fixed weights, a linear mixing strategy is adopted to construct hybrid weights, expressed as (9):

$$\omega_j^{\text{hybrid}} = m \cdot \omega_j^{\text{dynamic}} + (1 - m) \cdot \omega_j^{\text{fixed}}, \quad (9)$$

The fusion coefficient m plays a crucial role in determining the contribution of dynamic and fixed weights: when m approaches 1, the hybrid weights are biased towards dynamic weights; when m approaches 0, the hybrid weights are biased towards fixed weights [25]. In the assessment model, $m = 0.5$, which allows dynamic weights and fixed weights to share equal influence in damage assessment. Fixed weights anchor prior physical mechanisms, preventing misjudgment caused by single-variable dominance in dynamic weights due to parameter fluctuations. The mathematical implementation of this algorithm is formally described in Table 3.

Table 3. Interval-valued intuitionistic fuzzy weight calculation.

1:	Input: port data, thresholds,
2:	$\omega_j^{\text{dynamic}}$ matrix $\leftarrow$ initialize zero matrix of size ports 'number' $\times$ n
3:	$\omega_j^{\text{fixed}} \leftarrow [a_1, a_2, a_3, a_4]$
4:	$m \leftarrow 0.5$
5:	for i from 1 to ports' number do
6:	calculate $P_{\max}, E_{\text{pulse}}, I_{\max}, V_{\max}$ from port data
7:	for j from 1 to n do
8:	generate IVIFN: $[\mu_L, \mu_U], [\nu_L, \nu_U]$ using Equations (1), (3) and (4) with ν from the same $\delta(x)$ model
9:	$\pi_L \leftarrow 1 - \mu_U - \nu_U$
10:	$\pi_U \leftarrow 1 - \mu_L - \nu_L$
11:	get h_j
12:	end for
13:	$\omega_j^{\text{dynamic}} \leftarrow (1 - [h_1, h_2, h_3, h_4]) / \text{sum}(1 - [h_1, h_2, h_3, h_4])$
14:	$\omega_j^{\text{hybrid}} \leftarrow m \times \omega_j^{\text{dynamic}} + (1 - m) \times \omega_j^{\text{fixed}}$
15:	ω_j^{hybrid} matrix ($j, :$) $\leftarrow \omega_j^{\text{hybrid}}$
16:	end for
17:	Output: ω^{hybrid} matrix

To extract the damage probability information that can be used for weighted fusion from it, a damage reasoning mechanism based on the exponential response function is designed. The following equation defines the nonlinear mapping function:

$$P_j = 1 - \exp\left(-n \cdot \frac{|x|}{x_{\text{threshold}} \cdot S_m}\right), \quad (10)$$

where P_j denotes the partial damage probability corresponding to the j -th electrical parameter, and n is a regulatory parameter set to 1 in this paper. S_m is a safety margin coefficient modulating the slope of the exponential mapping from membership level to partial damage probability, controlling the growth rate of P_j . It is an empirically set safety margin coefficient, typically adopted as 1.1 in engineering, reflecting the actual interference intensity of the external electric field on the circuit after penetrating the protective layer. In this study, $n = 1$; hybrid coefficient $m = 0.5$ in Equation (9); IVIF width constants $\alpha = 0.05$ and $\beta = 0.15$ in Equation (3); and operational level bands [0.3, 0.6, 0.9] are engineering defaults grounded in the literature-informed values summarized in Table 4, with perturbation results reported in Section 3.4.

$$P_{\text{total}} = \sum_{j=1}^4 \omega_j^{\text{hybrid}} \cdot P_j, \quad (11)$$

where P_{total} represents the comprehensive damage probability for this port, which not only reflects the degree of over-limit of each electronic parameter itself, but also integrates their relative importance in a multi-index background [25].

Table 4. Literature-informed engineering defaults for assessment parameters.

Parameter/Threshold Set	Value Used	Literature/Rationale
Peak power thresholds (a, b, c)	0.1, 0.5, 1.0 W	Coupled power exceedance routes [9]; port peak metrics
Pulse energy thresholds (a, b, c)	50 ns, 1 μ s, 4 μ s equiv.	HPM pulse duration effects [6,7]
Peak current thresholds (a, b, c)	0.1, 0.25, 1.0 A	Device terminal stress in HPM tests [9]; SC2272 nets
Peak voltage thresholds (a, b, c)	3.6, 5.0, 15.0 V	LNA/CMOS HPM upset reports [3–5]
Safety margin S_m	1.1	Post-shielding field attenuation margin (engineering practice)
Hybrid coefficient m	0.5	Balanced dynamic/fixed weights; Section 3.4 m sweep
IVIF width α, β	0.05, 0.15	Interval hesitation width [23]; Section 3.4 α/β sweep
Level bands	0.3, 0.6, 0.9	Four-tier operational risk partition; Section 3.4

3. Results and Analysis

To analyze the differences in damage risk of the seeker in different bands under the action of high-power electromagnetic pulses, this paper conducts field-circuit simulations, selects typical L-band and X-band simulation data, and builds their respective interval fuzzy matrices based on the aforementioned IVIF modeling model. The dynamic weights of each parameter are obtained based on the fuzzy matrices. A single probability is output by using the hybrid weight mechanism. Finally, the damage probability is output, and damage is determined according to the grade mechanism. Notably, there are distinct differences in response characteristics between the L-band and X-band, which illustrate the influence of frequency band variations on damage tendency assessment. The specific results are as follows.

To contextualize the proposed IVIF-hybrid assessment framework, Section 3.3 compares it with fixed threshold (B1), crisp fuzzy (B2), entropy-only (B3), and fixed weight (B4)

damage assessment rules using identical electromagnetic simulation software-derived port metrics [9–12].

3.1. Field-Circuit Simulation Results

Electric-field magnitude snapshots at L-band 1.2 GHz and X-band 10.3 GHz are presented in Figure 4.

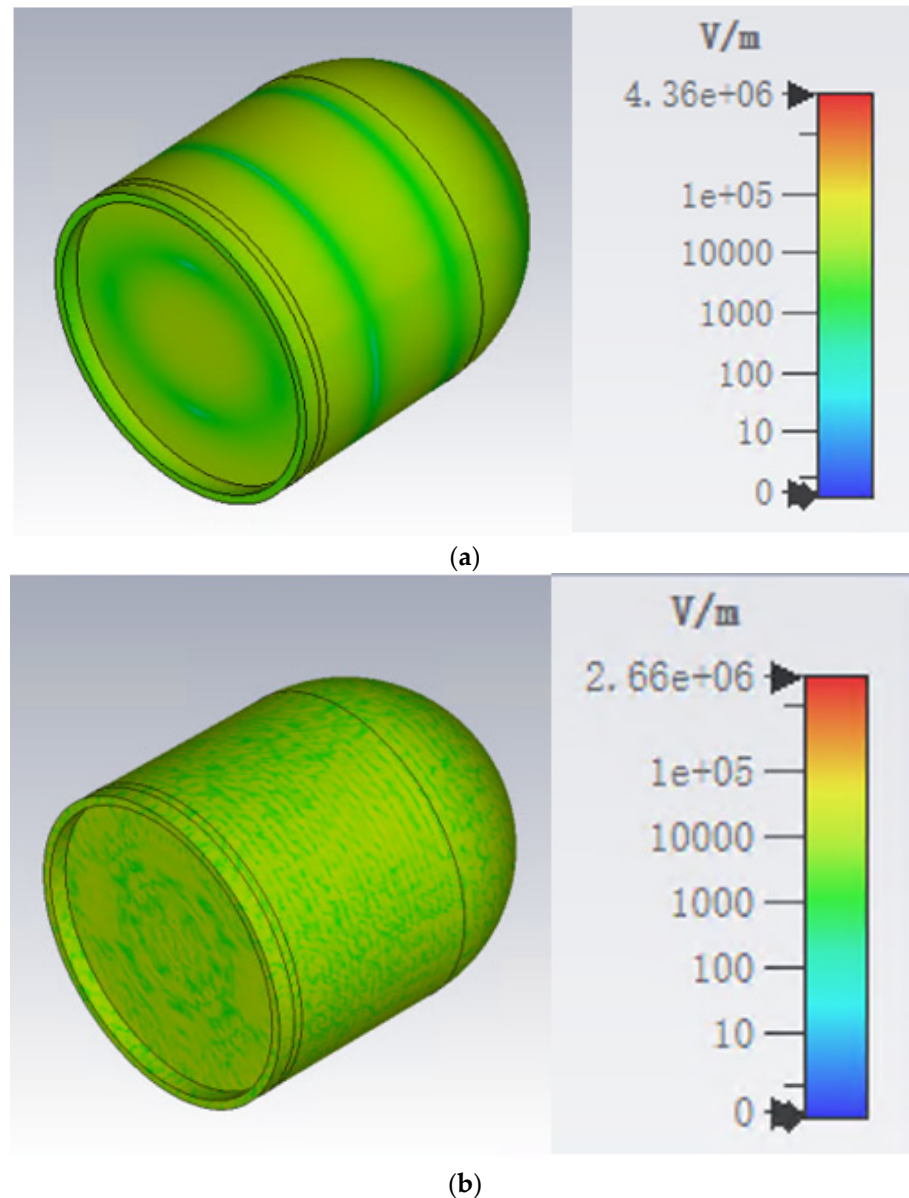


Figure 4. Electric-field magnitude snapshot. (a) L-band 1.2 GHz. (b) X-band 10.3 GHz.

In Figure 4a, the L-band field aggregates over a broad surface zone with a peak magnitude of 4.36×10^6 V/m; Figure 4b reports 2.66×10^6 V/m at 10.3 GHz, indicating stronger low-frequency coupling into the seeker enclosure under the same 25 kV/m excitation. Port voltage and instantaneous-power waveforms for representative L- and X-band ports are shown in Figure 5. Across the X-band panels, all ports exhibit brief high-amplitude spikes near 20 ns; Port 7 peaks at about 32 V, exceeding the voltage safety threshold, yet the pulse width remains short. Multi-parameter IVIF assessment is therefore used rather than peak voltage alone to avoid one-sided damage calls.

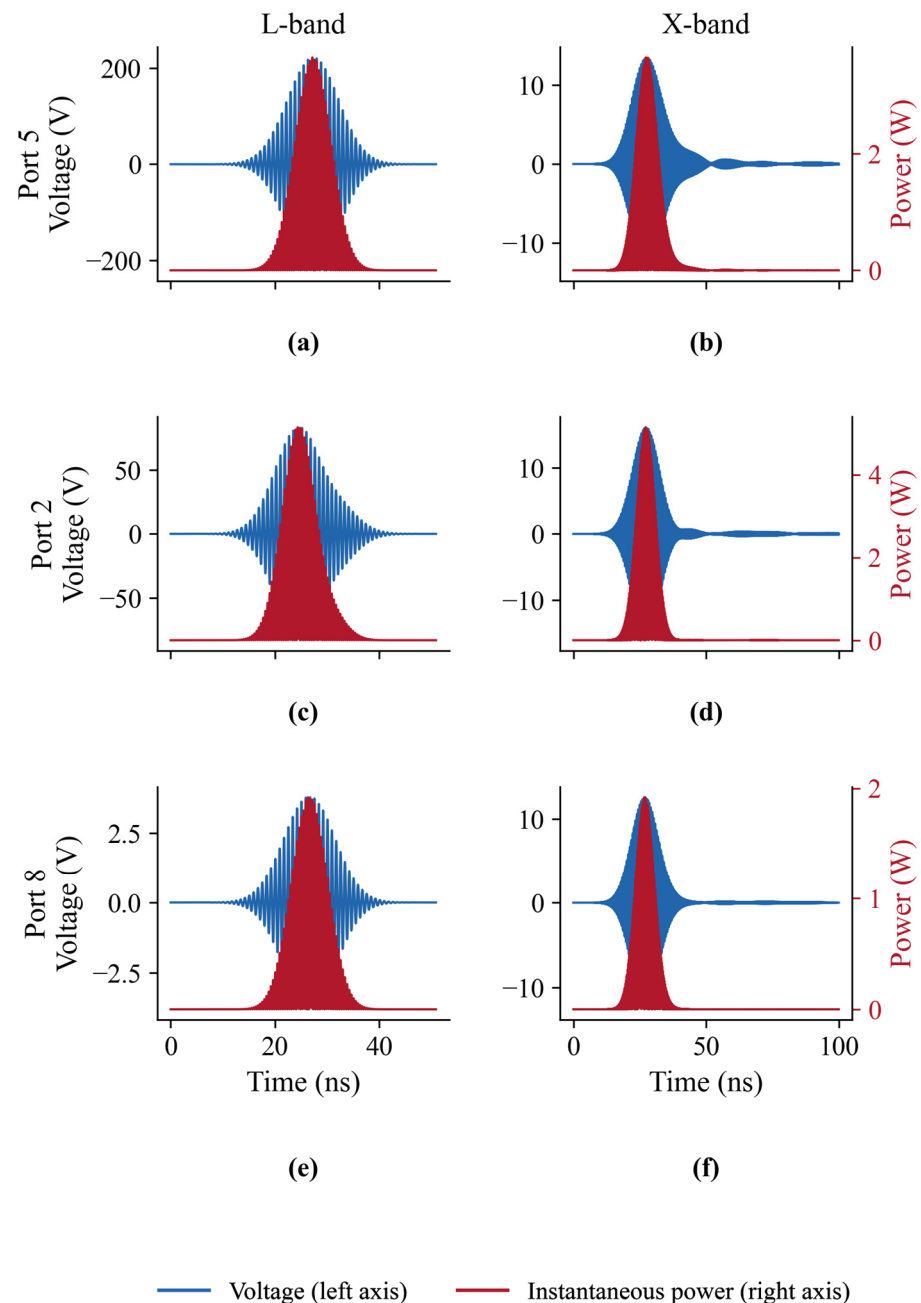


Figure 5. Port voltage and instantaneous power. (a,c,e) L-band Ports 5, 2, 8; (b,d,f) X-band Ports 5, 2, 8.

3.2. Results Analysis Based on the Damage Assessment Model

Composite damage probabilities for the L-band and X-band seekers under the IVIF-hybrid rule (B0) are summarized in Figure 6.

In Figure 6a, the damage probability values across the ports show obvious volatility. Port 5 has a significantly higher damage probability of 0.85, forming a prominent peak in the distribution, which indicates that this port is more sensitive to the comprehensive influence of electrical parameters and thus more prone to damage. Port 8 of the L-band has a damage probability of 0.07, much lower than that of other ports. The X-band seeker exhibits a relatively stable damage probability distribution across its ports. The overall probability values are generally lower than those of the L-band in most cases. Port 6 of the X-band has a composite damage probability of 0.096. There are no drastic fluctuations, reflecting a more uniform response of the X-band to changes in the electrical parameters

across multiple ports. According to the probability of Port 8, the results also confirm that whether in the L-band or X-band, the electromagnetic waves coupled into the LNA are weak, so the impact of out-of-band electromagnetic waves on the LNA is relatively minor. In contrast, the pins on the other chip are affected relatively more significantly, especially in the L-band. Port counts by discrete damage level for the L- and X-band seekers are compared in Figure 7.

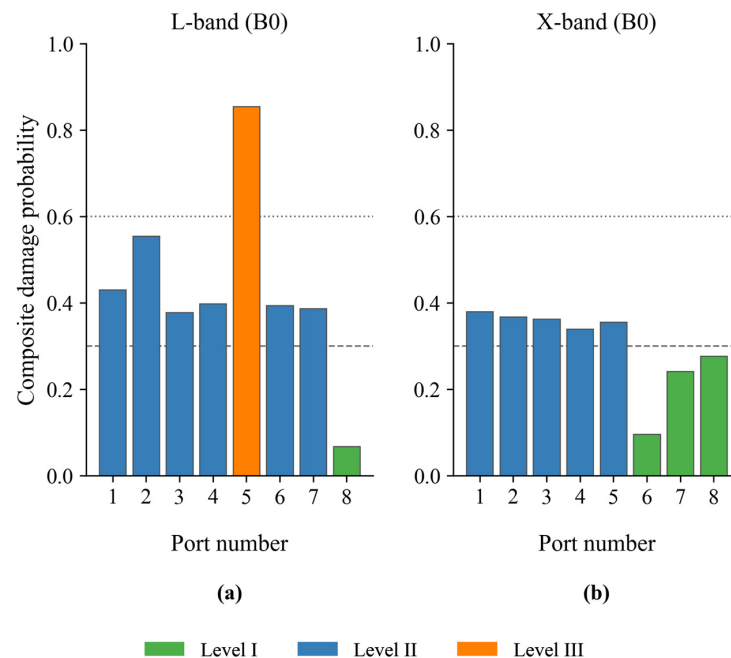


Figure 6. Composite damage probability by port (B0). (a) L-band. (b) X-band.

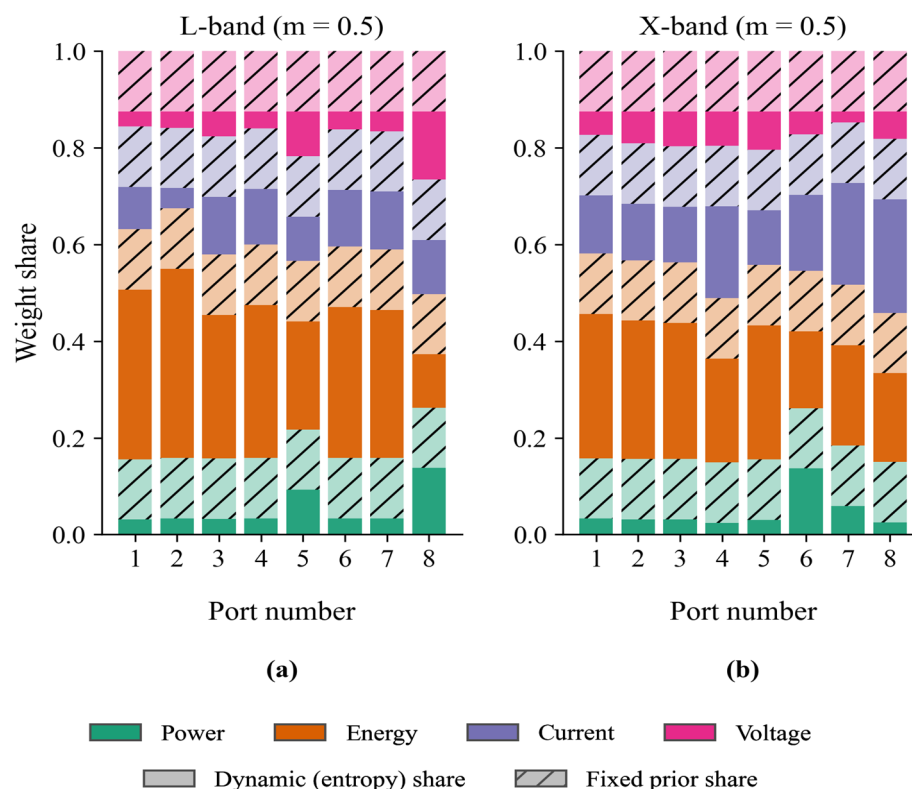


Figure 7. Port counts by damage level. (a) L-band. (b) X-band.

Figure 7a shows most Lband ports at Levels II–III with one Level-III port, whereas Figure 7b shows X-band ports concentrated at Levels I–II, confirming higher simulated L-band level spread under identical excitation. Port-wise IVIF membership and non-membership intervals for the L- and X-band seekers are listed in Tables 5 and 6.

Table 5. Fuzzy matrix of seeker in L-band.

Indicators	Port1	Port2	Port3	Port4
Power	<[0.975, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>
Energy	<[0.000, 0.193], [0.614, 0.807]>	<[0.476, 0.674], [0.128, 0.326]>	<[0.000, 0.096], [0.709, 0.900]>	<[0.000, 0.110], [0.698, 0.890]>
Current	<[0.925, 1.000], [0.000, 0.000]>	<[0.969, 1.000], [0.000, 0.000]>	<[0.902, 1.000], [0.000, 0.000]>	<[0.908, 1.000], [0.000, 0.000]>
Voltage	<[0.975, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>	<[0.960, 1.000], [0.000, 0.000]>	<[0.974, 1.000], [0.000, 0.000]>
Indicators	Port5	Port6	Port7	Port8
Power	<[0.975, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>	<[0.377, 0.569], [0.239, 0.431]>
Energy	<[0.937, 1.000], [0.000, 0.000]>	<[0.000, 0.101], [0.707, 0.899]>	<[0.000, 0.096], [0.708, 0.900]>	<[0.000, 0.095], [0.709, 0.900]>
Current	<[0.975, 1.000], [0.000, 0.000]>	<[0.906, 1.000], [0.000, 0.000]>	<[0.904, 1.000], [0.000, 0.000]>	<[0.000, 0.097], [0.706, 0.900]>
Voltage	<[0.975, 1.000], [0.000, 0.000]>	<[0.972, 1.000], [0.000, 0.000]>	<[0.969, 1.000], [0.000, 0.000]>	<[0.045, 0.243], [0.558, 0.757]>

Table 6. Fuzzy matrix of seeker in X-band.

Indicators	Port1	Port2	Port3	Port4
Power	<[0.975, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>
Energy	<[0.000, 0.096], [0.709, 0.900]>	<[0.000, 0.096], [0.709, 0.900]>	<[0.000, 0.096], [0.709, 0.900]>	<[0.000, 0.095], [0.709, 0.900]>
Current	<[0.902, 1.000], [0.000, 0.000]>	<[0.900, 1.000], [0.000, 0.000]>	<[0.900, 1.000], [0.000, 0.000]>	<[0.756, 0.956], [0.000, 0.044]>
Voltage	<[0.962, 1.000], [0.000, 0.000]>	<[0.946, 1.000], [0.000, 0.000]>	<[0.939, 1.000], [0.000, 0.000]>	<[0.920, 1.000], [0.000, 0.000]>
Indicators	Port5	Port6	Port7	Port8
Power	<[0.975, 1.000], [0.000, 0.000]>	<[0.000, 0.080], [0.740, 0.900]>	<[0.933, 1.000], [0.000, 0.000]>	<[0.969, 1.000], [0.000, 0.000]>
Energy	<[0.000, 0.096], [0.709, 0.900]>	<[0.000, 0.095], [0.709, 0.900]>	<[0.000, 0.095], [0.709, 0.900]>	<[0.000, 0.095], [0.709, 0.900]>
Current	<[0.900, 1.000], [0.000, 0.000]>	<[0.000, 0.094], [0.711, 0.900]>	<[0.000, 0.097], [0.706, 0.900]>	<[0.254, 0.452], [0.349, 0.548]>
Voltage	<[0.932, 1.000], [0.000, 0.000]>	<[0.929, 1.000], [0.000, 0.000]>	<[0.975, 1.000], [0.000, 0.000]>	<[0.927, 1.000], [0.000, 0.000]>

From Tables 3 and 4, L-band ports show concentrated high- μ intervals on power and voltage for Ports 1–7, while X-band Ports 7–8 retain wider ν bounds on power and energy, indicating stronger cross-indicator hesitation before weighting. Hybrid weight vectors

from Equation (9) are decomposed by port in Figure 8; Figure 8a shows the L-band and Figure 8b shows the X-band.

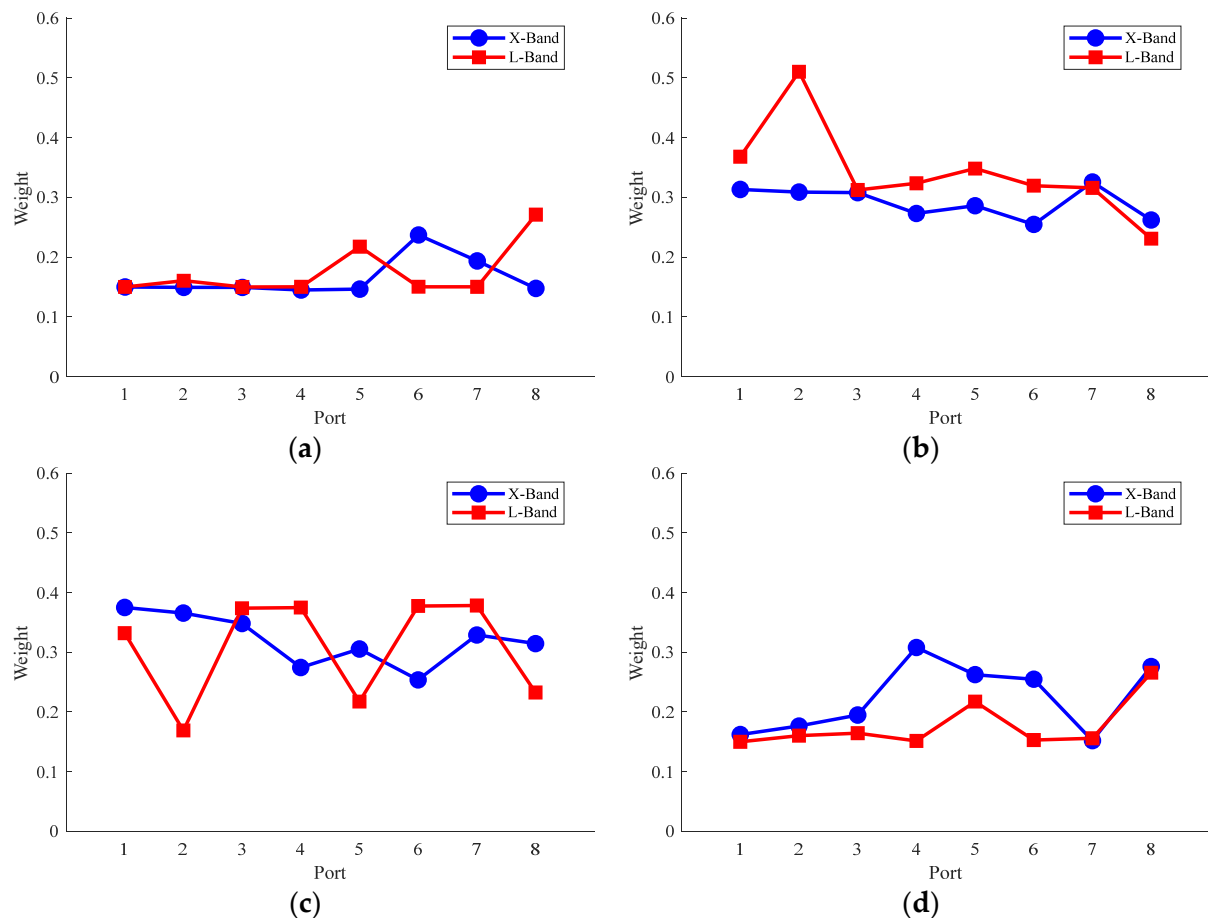


Figure 8. Hybrid weight decomposition by port. (a) Power. (b) Energy. (c) Current. (d) Voltage.

In Figure 8, L-band weight variability is most prominent in current, showing the largest fluctuations across ports with distinct highs and lows. Energy maintains a slightly higher and stable proportion relative to power and current, with minimal fluctuation. Power exhibits moderate stability, with smaller fluctuations than current but less consistency than energy, reflecting its steady secondary contribution to damage assessment under fuzzy characteristics. In the X-band, voltage and current both show small fluctuations in weights across ports. Energy maintains a consistent proportion without obvious peaks, aligning with the overall stable trend. Power remains at relatively low weights, with minor variations, confirming its limited impact. This stability across indicators, especially in power and voltage, stems from balanced membership and non-membership intervals in fuzzy modeling, resulting in a uniform influence on damage assessment.

Overall, the L-band case shows stronger Port 5 concentration and wider level spread across ports, while the X-band case exhibits milder port-to-port contrasts and wider v bounds on several indicators. The IVIF assessment model established in this paper can effectively reflect differences in the damage tendency of devices across frequency bands under multi-parameter excitation and has good discrimination ability and structural adaptability. The fuzzy matrix analysis results also provide important support for the subsequent hybrid weight configuration and damage probability integration. The band difference is clear: the L-band features significant current fluctuations and a high weight proportion of energy and voltage, while the X-band shows overall stability in power, voltage, and energy. This verifies the hybrid weighting mechanism's effectiveness in capturing fuzzy

characteristic differences, with stable indicators reflecting their reliable contribution to damage assessment.

3.3. Comparative Evaluation Against Baseline Assessment Methods

Using the same port metrics and safety thresholds defined in Sections 2.2 and 2.3, four alternative damage assessment rules (B1–B4) are compared with the proposed IVIF-hybrid assessment pipeline (B0) on all eight observation ports. Independent physical damage labels are unavailable; baselines follow conventional threshold-based and fuzzy comprehensive assessment routes in HPM and equipment damage evaluation [9–12] and are treated as alternative assessment rules, not calibrated ground truth. The comparison therefore evaluates relative assessment behavior under identical simulation inputs rather than absolute probability accuracy against measured failure data.

Table 7 summarizes comparative assessment metrics aligned with the multi-port damage assessment objective in Section 2. The Port 8 probability range P_{range} measures port-level discrimination among assessment outputs; the L-band minus X-band mean gap, together with Port 5 (L) and Port 6 (X) composite probabilities, tests consistency with the field-circuit narrative in Section 3.2; and structural ablation via B2–B4 is evaluated using discrete level counts in Table 7 and port-wise level assignments in Table 8. Relative to the primary baseline B1 (fixed threshold pass/fail assessment), B0 preserves graded port-to-port contrast: five of eight L-band ports remain at intermediate probabilities rather than collapsing to $p = 0.5$, while Port 5 (L) stays at 0.855 and Port 6 (X) at 0.096. For ablations, B3 collapses multi-port grading because only two L-band ports reach Level II or above and zero X-band ports reach Level II or above despite a $P_{\text{range_L}}$ comparable to B0; B2 retains seven Level-II+L-band ports but assigns Level III to Ports 1 and 2, where B0 remains at Level II after IVIF intervals are collapsed to crisp membership with equal fixed weights. Higher mean P under B2 reflects a different scoring rule rather than closer agreement with a preferred assessment output.

Table 7. B0–B3 comparative metrics (eight ports; identical electromagnetic simulation software inputs).

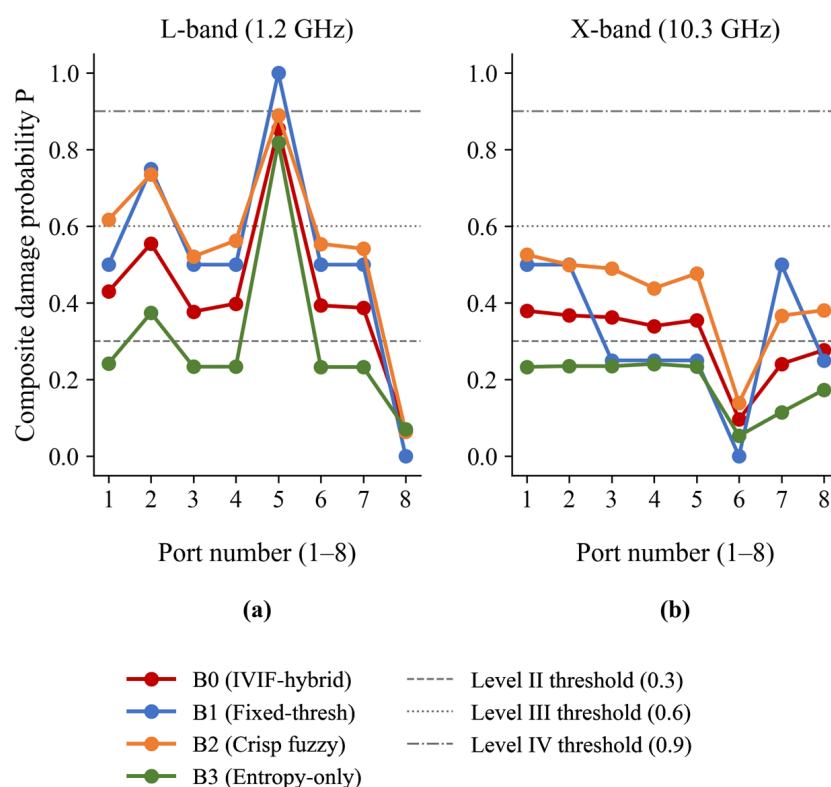
Method	Code	$P_{\text{rng L}}$	L – X Mean	Port5 L	Port6 X	$N \geq \text{II (L)}$	$N \geq \text{III (L)}$	$N \geq \text{II (X)}$
IVIF-hybrid	B0	0.787	0.131	0.855	0.096	7.000	1.000	5.000
Fixed-thresh	B1	1.000	0.219	1.000	0.000	7.000	2.000	3.000
Crisp fuzzy	B2	0.827	0.146	0.891	0.140	7.000	3.000	7.000
Entropy-only	B3	0.747	0.115	0.818	0.053	2.000	1.000	0.000

B2–B4 ablate components of the proposed assessment chain: B2 removes IVIF intervals and retains crisp membership only; B3 removes fixed and hybrid weights and uses entropy-driven weights only; B4 removes entropy adaptation and uses fixed weights only. B4 numerically overlaps B2 in the present case and is omitted from the Section 3.3 baseline probability plot for clarity. Read together with Tables 7 and 8, these ablations show that interval-valued fuzziness and hybrid weighting are non-redundant for multi-port damage level assessment rather than optional extensions of fixed threshold rules. In the present case, B0 and B2 agree on the Port 5 hotspot and on seven Level-II+L-band ports; the ablation comparison therefore tests non-redundancy of IVIF interval expression and hybrid weighting rather than superior scalar accuracy of B0 over B2. Hybrid coefficient sensitivity—including the m sweep where the L/X mean gap changes but Port 5 (L) stays near 0.85 at Level III—is reported in Section 3.4.

Table 8. Port-wise damage levels (I–IV) for B0–B3.

Band	Port	B0	B1	B2	B3
L	1	II	II	III	I
L	2	II	III	III	II
L	3	II	II	II	I
L	4	II	II	II	I
L	5	III	IV	III	III
L	6	II	II	II	I
L	7	II	II	II	I
L	8	I	I	I	I
X	1	II	II	II	I
X	2	II	II	II	I
X	3	II	I	II	I
X	4	II	I	II	I
X	5	II	I	II	I
X	6	I	I	I	I
X	7	I	II	II	I
X	8	I	I	II	I

B0 maintains a pronounced L-band peak at Port 5 (0.855) and a low X-band response at Port 6 (0.096) in Figure 9, consistent with Section 3.2, whereas B1 collapses these distinctions to coarse pass/fail assessment levels. The compressed B3 curves coincide with the level collapse reported in Tables 7 and 8, whereas B2 follows a similar port pattern with uniformly higher P and additional Level-III assignments on non-dominant ports. Figure 10 summarizes the corresponding discrete Levels I–IV for B0–B3 across all eight ports. Overall, the IVIF-hybrid framework supports simulation-based multi-port HPM damage assessment with finer port discrimination and retained uncertainty structure than fixed threshold assessment alone.

**Figure 9.** Composite damage probability by port. (a) L-band. (b) X-band.

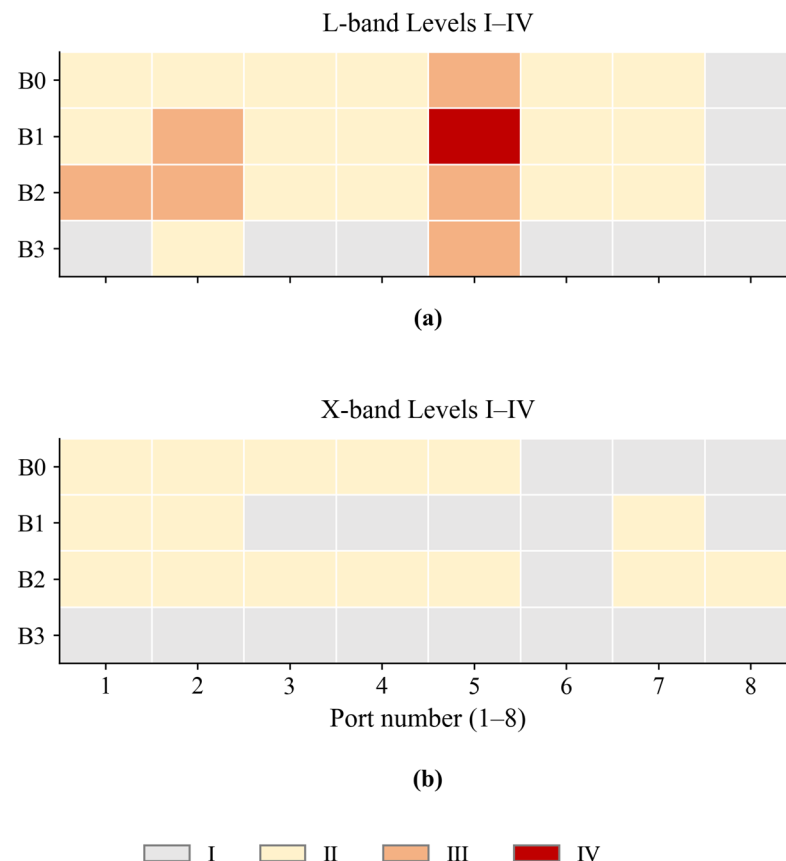


Figure 10. Discrete damage levels (I–IV). (a) L-band. (b) X-band.

3.4. Parameter Sensitivity Analysis

Because damage labels are simulation-based, sensitivity analysis examines whether port rankings and Port 5 (L-band) damage levels remain stable when hybrid coefficient m , IVIF width constants α and β , level-band thresholds $[0.3, 0.6, 0.9]$, and safety margin S_m are perturbed within engineering ranges. Table 9 lists the perturbed scenarios; Figure 11 traces Port 5 composite probability under S_m sweeps. Although the L/X mean-probability gap varies with m , Port 5 (L) remains at Level III and near 0.85 across the m sweep, supporting $m = 0.5$ as an engineering default that balances fixed and entropy-driven weights; S_m and level-band perturbations leave Port 5 at Level III except when all thresholds are shifted downward by 0.05 (Level IV). Figure 11 shows Port 5 (L) composite probability remaining near 0.85 for S_m between 1.0 and 1.2 while level-band shifts change the assigned level only when all thresholds are lowered by 0.05. Perturbations of the IVIF width constants $\alpha \in \{0.03, 0.05, 0.07\}$ ($\beta = 0.15$) and $\beta \in \{0.10, 0.15, 0.20\}$ ($\alpha = 0.05$) leave Port 5 (L) composite probability between 0.839 and 0.864 and Level III unchanged, indicating robust hotspot ranking with respect to IVIF width settings within this band.

Table 9. Sensitivity of Port 5 (L) and L/X mean gap.

Case	m	S_m	$t1$	$t2$	$t3$	P5	Lvl	L – X μ
$m = 0.0$	0.000	1.100	0.3	0.6	0.9	0.891	III	0.146
$m = 0.5$	0.500	1.100	0.3	0.6	0.9	0.855	III	0.131
$m = 1.0$	1.000	1.100	0.3	0.6	0.9	0.818	III	0.115
$S_m = 1.0$	0.500	1.000	0.3	0.6	0.9	0.870	III	0.130
$S_m = 1.1$	0.500	1.100	0.3	0.6	0.9	0.855	III	0.131
$S_m = 1.2$	0.500	1.200	0.3	0.6	0.9	0.840	III	0.131
levels = base	0.500	1.100	0.3	0.6	0.9	0.855	III	0.131

Table 9. Cont.

Case	m	S_m	$t1$	$t2$	$t3$	P5	Lvl	$L - X \mu$
levels = -0.05	0.500	1.100	0.25	0.55	0.85	0.855	IV	0.131
levels = $+0.05$	0.500	1.100	0.35	0.65	0.95	0.855	III	0.131
alpha = 0.03	0.500	1.100	0.3	0.6	0.9	0.839	III	0.124
alpha = 0.05	0.500	1.100	0.3	0.6	0.9	0.855	III	0.131
alpha = 0.07	0.500	1.100	0.3	0.6	0.9	0.863	III	0.135
beta = 0.10	0.500	1.100	0.3	0.6	0.9	0.864	III	0.134
beta = 0.20	0.500	1.100	0.3	0.6	0.9	0.847	III	0.128

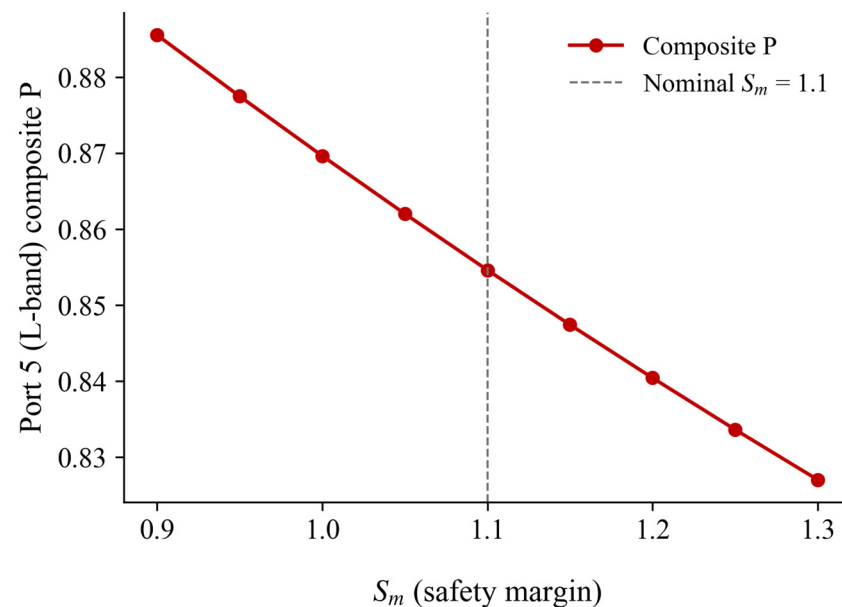


Figure 11. Port 5 (L) composite probability under m , S_m , and level-band perturbations. All figures will be supplied at journal-required resolution in the final production files.

4. Conclusions

This study presents a hybrid weighted assessment model based on IVIF for damage assessment of seekers under HPM exposure. By extracting key electrical parameters via field-circuit coupling simulations, a multi-index fuzzy matrix is constructed to quantify uncertainties arising from electromagnetic measurement errors and device failure thresholds. An entropy-driven dynamic weighting mechanism based on IVIF enables adaptive prioritization of indicators. Meanwhile, an exponential damage mapping function completes multi-parameter probability fusion and grade determination, forming a closed-loop assessment from electrical parameters to damage levels. Simulation-based results indicate the following: Under the stated excitation, L-band Port 5 reaches the highest composite probability (0.855), whereas X-band Port 6 remains low (0.096), consistent with the field circuit patterns in Section 3.2. Distinct multi-level damage characteristics are observed, and different ports exhibit distinct damage situations under high-intensity excitation. Furthermore, the framework integrates parameters with interval fuzziness and dynamic weighting mechanisms. By extending hybrid weights based on dynamic weighting, the influence of the parameters is effectively constrained within a reasonable range in the assessment. This framework offers a simulation-based workflow for multi-port HPM damage prioritization under the fixed L/X scenario described in Section 2.2. Extension to additional excitation levels, incidence angles, or seeker configurations can be pursued in future simulation studies; threshold sets can be updated when datasheet or bench data become available for a given platform.

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