Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

When Does Signal-to-Noise Ratio Modeling Pay Off in HF Receiving Antenna Selection?

A Monte Carlo Comparison with NEC2 Gain

Sergio Zuniga-Jara
Amateur Radio Callsign: XQ2CG
Universidad Católica del Norte
Coquimbo, Chile

***Abstract*—High-frequency receiving antennas are usually compared by electromagnetic gain, although reception depends on the signal-to-noise ratio delivered to the receiver. This study asks when modeling that ratio improves antenna selection beyond simple NEC2 gain. Four passive antennas were modeled across eight amateur bands, and a Monte Carlo experiment with 2.4 million environmental realizations, three noise scenarios, and 32 partial-information selection rules compared dynamic and fixed selection, with exact Shapley values attributing the gains. When the antenna can be switched for every realization, complete modeling improved simulated mean performance by 1.382 decibels over total NEC2 gain and changed the chosen antenna in 35.0 percent of cases, but polarization resolution, which NEC2 already supplies, accounted for 83.4 percent of this gain. Beyond polarization-resolved gain, noise coupling and impedance matching added only 0.243 decibels. For a single fixed antenna, complete modeling improved selection by just 0.1305 decibels, while fixed NEC2 selection stayed 3.594 decibels below the ideal switching benchmark. Modeling pays off mainly when polarization is resolved, when several antennas can be switched, and when the candidate set is chosen with care; refining the model of one fixed antenna yields little.**

Keywords—HF receiving antennas; NEC2; signal-to-noise ratio; polarization; Shapley values; antenna selection

I. Introduction

High-frequency (HF) receiving antennas are conventionally compared using gain, directivity, radiation patterns, impedance, and efficiency [1]. Numerical Electromagnetics Code (NEC) simulations [2] supply these characteristics and support comparisons among antenna geometries. However, gain alone does not determine reception quality. The relevant system-level criterion is the signal-to-noise ratio (SNR), which depends on both the desired signal and the noise delivered to the receiver: an antenna with lower directional gain may deliver better SNR if it collects proportionally less external noise. This matters at HF, where atmospheric, man-made, and galactic noise can dominate receiver noise. Recommendation ITU-R P.372 [3] gives statistical estimates of these components but does not specify their local angular distributions.

Previous work has examined direction-sensitive HF noise and its effect on antenna selection [4], [5], and the influence of antenna efficiency and impedance mismatch on realized receiving-system noise performance [6]. Conventional antenna and receiver theory links gain, impedance, noise temperature, and delivered SNR [1], [7]. The physical importance of a parameter, however, does not establish its incremental value for choosing an antenna: a parameter can change received power without changing the preferred antenna.

This paper therefore asks a practical question: when is it worth going beyond simple NEC2 gain, and by how much does an SNR model improve the choice of a passive HF receiving antenna? Because NEC2 already supplies horizontal and vertical gain components, the analysis separates the benefit of resolving signal polarization from the additional benefit of full receiving-system SNR modeling. The contributions are:

- *Methodological:* antenna evaluation is posed as a selection problem, and the value of five information categories is attributed with exact Shapley values over 32 partial-information rules, using common-environment Monte Carlo comparisons.
- *Quantitative:* under the simulated conditions, ideal switching among antennas gains 1.382 dB over total NEC2 gain, but 83.4% of this comes from polarization, which NEC2 already provides; complete SNR modeling adds only 0.243 dB beyond it, and only 0.1305 dB for a single fixed antenna.
- *Practical:* a decision guide (Section IV) states for which station configurations SNR modeling is worth the effort.

II. Methodology

A. Antennas and Experimental Design

Four passive HF receiving antennas were evaluated: a horizontal wire dipole, a triangular wire loop, a vertical ground-plane antenna, and a horizontal three-element Yagi. Electromagnetic modeling used nec2c with ground parameters $\varepsilon_r = 13$ and $\sigma = 0.005$ S/m. Eight frequencies were analyzed (3.6, 7.1, 10.1, 14.2, 18.1, 21.2, 24.9, and 28.5 MHz), corresponding to the 80, 40, 30, 20, 17, 15, 12, and 10 m amateur bands. NEC2 outputs comprised total gain, horizontal and vertical gain components, complex input impedance, and the power budget (radiation efficiency). Upper-hemisphere patterns were sampled every 5° in polar angle and 10° in azimuth. The geometries were kept at all frequencies, including outside their nominal design bands, so the experiment compares specified configurations, not independently optimized antennas.

Each realization draws the signal elevation (band-specific uniform range, Table VI) and azimuth (uniform), the horizontal power fraction $p_H \sim U(0,1)$, the month and UTC hour (uniform), independent standard-normal deviates for the three noise-component levels, a receiver noise figure U(8,16) dB, a line loss U(0,2) dB, and the angular parameters of the noise scenario. All four antennas are evaluated under exactly the same realization.

Three external-noise scenarios were considered (Table VII). In the isotropic scenario (iso), all noise components are isotropic

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

and unpolarized. In the directional artificial scenario (hor), the man-made component is concentrated at low elevation and mostly vertically polarized. In the directional atmospheric scenario (atm), the atmospheric component is concentrated at low elevation with azimuthal modulation, but only at night and up to 10.2 MHz (80, 40, and 30 m); in the other bands atm reduces to isotropic noise. These angular laws are modeling assumptions, not P.372 predictions. Each frequency-by-scenario cell holds 100,000 realizations; the 24 cells give 2.4 million realizations and 9.6 million antenna-SNR evaluations (Table I).

TABLE I. PRINCIPAL SIMULATION ASSUMPTIONS

Parameter	Specification
Antennas	Dipole, triangular loop, vertical, three-element Yagi
Frequencies	Eight bands, 3.6–28.5 MHz
Reference site	Antofagasta, Chile (23.6° S, 70.4° W)
Signal	Uniform azimuth; band-specific elevation; $p_H \sim$ U(0,1)
External noise	ITU-R P.372-14 (code 14.3), residential; month and UTC hour uniform
Receiver NF; line loss	U(8,16) dB; U(0,2) dB
Realizations	100,000 per cell × 24 cells = 2,400,000
Rules; master seed	32 partial-information rules; 20261117

NF: receiver noise figure.

B. Receiving-System SNR Model

SNR is computed on a relative scale: incident flux density, bandwidth, and Boltzmann's constant are common to all antennas and cancel. For antenna a,

$$\mathrm{SNR}_a = \frac{\tau_a G_{\mathrm{co},a}}{D_a} \tag{1}$$

where the denominator is

$$D_a = \tau_a \left(\sum_{i\in\{A,M,G\}} F_i g_{i,a} + \left(f_{\mathrm{str},a} + f_{\mathrm{gnd},a}\right) \frac{T_{\mathrm{phys}}}{T_0} \right) + C \tag{2}$$

with T_0 = 288 K and T_{phys} = 290 K (uniform for structure, ground, and line), and $C = (L-1)T_{\mathrm{phys}}/T_0 + L(F_r-1)(290/T_0)$ the line (loss factor $L \geq 1$) and receiver (noise factor F_r [8]) terms, common to all antennas in a realization. The copolar gain is $G_{\mathrm{co},a} = p_H G_{H,a} + (1-p_H)G_{V,a}$, where G_H and G_V are NEC2 power gains toward the signal referred to the input power; they therefore already include structure dissipation and ground absorption, and the numerator is not corrected again. The mismatch factor is $\tau_a = 4R_a Z_0/[(R_a+Z_0)^2+X_a^2]$ with Z_0 = 50 Ω and no tuner, and τ_a multiplies antenna-side signal and noise only. The dissipated fractions are $f_{\mathrm{str},a} = 1 - \eta_{\mathrm{str},a}$ (structure and loads) and $f_{\mathrm{gnd},a} = \eta_{\mathrm{str},a} - \eta_{\mathrm{sky},a}$ (ground), where $\eta_{\mathrm{sky},a}$ is the pattern gain integrated over the upper hemisphere divided by 4π.

External noise comprises atmospheric, man-made, and galactic components $i \in \{A, M, G\}$ with realized levels $F_i = 10\text{^}\{(m_i+z_i\ D_i/Z_{90})/10\}$, where m_i is the P.372 median, z_i an independent standard-normal deviate, D_i the upper or lower decile deviation, and Z_{90} the corresponding standard-normal decile value. The coupling of antenna a to component i is

$$g_{i,a} = \frac{\langle p_{\mathrm{H},i} G_{\mathrm{H},a} + p_{\mathrm{V},i} G_{\mathrm{V},a} \rangle_w}{\langle p_{\mathrm{V},i} D_{\mathrm{ref}} \rangle_w} \tag{3}$$

with $D_{\mathrm{ref}} = 3\cos^2(\mathrm{el})$ and weight $w(\Omega) = T_{b,i}(\Omega)\cos(\mathrm{el})$, normalized to the P.372 reference antenna (lossless short vertical monopole over perfect ground), so that g = 1 for that monopole and $g = \eta_{\mathrm{sky}}$ for isotropic unpolarized noise. $T_{b,i}$ is the angular brightness law of the scenario (Table VII) and $p_{V,i}$ the vertical power fraction of the noise. Signal polarization uses horizontal and vertical power fractions; the patterns preserve the vertical power fraction but not the relative phase of the field components, so the model is an incoherent two-component approximation, not general vector polarization. The coupling normalization (unity for the reference monopole, and equal to the sky efficiency for isotropic unpolarized noise) and the equivalence of the denominator to a passive-network noise cascade were verified numerically on a reference monopole and representative NEC2 patterns.

C. Information Categories and Selection Rules

Five information categories are considered: $\mathcal{N}$ = {P, E, M, D, R}, namely polarization, efficiency, impedance matching, external-noise coupling, and receiver characteristics. Every subset $S \subseteq \mathcal{N}$ defines a partial-information selection rule, giving 2^5 = 32 rules. For rule S, antenna a receives the decision score $Q_a(S,\omega)$, where ω is one environmental realization: the SNR expression of Section II-B in which every variable of an unavailable category is replaced by a reference value common to all antennas (Table VIII), never by its realized value. These substitutions are heuristic decision rules, not Bayesian conditional-expectation policies, so additional information may have negative marginal contributions.

The baseline selects the antenna with the greatest total NEC2 gain toward the simulated signal direction,

$$a_\emptyset = \underset{a}{\mathrm{argmax}} G_{\mathrm{tot},a}, \quad G_{\mathrm{tot},a} = G_{\mathrm{H},a} + G_{\mathrm{V},a} \tag{4}$$

with components added on a linear-power scale [1]. It uses arrival direction but does not resolve the incident polarization. The polarization-resolved NEC2 criterion is

$$a_{\mathrm{NEC},P} = \underset{a}{\mathrm{argmax}} \left[p_H G_{\mathrm{H},a} + (1-p_H) G_{\mathrm{V},a} \right] \tag{5}$$

Under rule {P} only p_H, G_H, and G_V take realized values; τ, thermal noise, external noise, and receiver terms take reference values common to all antennas. The denominator D_a is then identical across antennas and the score is a monotone function of $G_{\mathrm{co},a}$, so {P} selects the same antenna as $a_{\mathrm{NEC},P}$; this equivalence was verified in the executed scoring function. By the same argument, R cannot alter the ranking when $S \subseteq$ {P, R}. Category D represents antenna-specific external-noise coupling; it includes the effect of replacing integrated antenna-specific noise collection by a common reference coupling when directional information is excluded, so its contribution need not vanish under isotropic noise.

D. Dynamic and Fixed Selection

Dynamic selection chooses an antenna separately for every realization, $a_S^{\mathrm{dyn}}(\omega) = \mathrm{argmax}_a\ Q_a(S,\omega)$. Under complete information the score is $Y_a(\omega) = 10 \log_{10} \mathrm{SNR}_a(\omega)$. This is an ideal adaptive benchmark, not an implemented switching system. Fixed selection requires one antenna per frequency-by-scenario cell. Each cell is divided equally into training and test samples, and the antenna with the highest mean training score is selected,

$$a_S^{\mathrm{fix}} = \underset{a}{\mathrm{argmax}} \frac{1}{N_{\mathrm{train}}} \sum_{\omega\in\mathcal{D}_{\mathrm{train}}} Q_a(S,\omega) \tag{6}$$

and performance is evaluated on independent test observations. Because scores are averaged in decibels, fixed selection maximizes mean logarithmic SNR rather than expected linear SNR.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

E. *Incremental Value and Shapley Attribution*

The incremental decision value of subset S relative to the total-gain baseline is $v(S) = \mathbb{E}[Y_S - Y_\emptyset]$, defined separately for dynamic and fixed selection. Exact Shapley values [9] allocate $v(\mathcal{N})$ among the categories,

$$\varphi_i = \sum_{S \subseteq \mathcal{N} \setminus \{i\}} w_S [v(S \cup \{i\}) - v(S)] \quad (7)$$

with weights $w_S = |S|!(n-|S|-1)!/n!$, $n = 5$, and $\Sigma_i \varphi_i = v(\mathcal{N})$. A decomposition conditional on polarization uses the same 32 values: for $T \subseteq \{E, M, D, R\}$ let

$$v_P(T) = v(T \cup \{P\}) - v(\{P\}) \quad (8)$$

This four-player game has total value $v(\mathcal{N}) - v(\{P\})$, and its Shapley values φ_i^P, computed as in (7) with $n = 4$, measure each remaining category's contribution once polarization is known. They need no new simulations and are not interchangeable with φ_i. Because {P} is equivalent to polarization-resolved NEC2 gain, this game attributes the benefit of SNR modeling over that stronger electromagnetic baseline. Dynamic confidence intervals used 2,000 paired-bootstrap replicates per cell; fixed-selection uncertainty used test-sample resampling and 300 repeated training-test partitions. Results are averaged over the 24 cells with equal weights. Confidence intervals quantify Monte Carlo uncertainty conditional on the simulated model, not uncertainty about its physical validity, and the conditional Shapley values are point estimates.

III. RESULTS

A. *Overall Selection Performance*

Under dynamic selection, complete SNR information changed the selected antenna in 35.03% of realizations and improved mean performance by 1.382 dB (Monte Carlo 95% CI: 1.378–1.385 dB). The geometric-mean linear SNR ratio is $10^{1.382/10} \approx 1.3745$, an improvement of about 37.45%. The mean of the cell-specific 95th percentiles of total-gain SNR loss was 7.63 dB.

For fixed selection the incremental improvement was only 0.1305 dB (conditional Monte Carlo 95% CI: 0.1264–0.1344 dB; repeated-partition interval 0.1263–0.1354 dB), about 3.05%. Relative to the ideal complete dynamic selector, the fixed NEC2 baseline showed a mean loss of 3.594 dB, which complete-information fixed selection reduced only to about 3.464 dB. The contrast between 1.382 dB (dynamic) and 0.1305 dB (fixed) is central to the practical value of additional information.

B. *Performance of Information Subsets*

TABLE II. PERFORMANCE OF SELECTED INFORMATION RULES

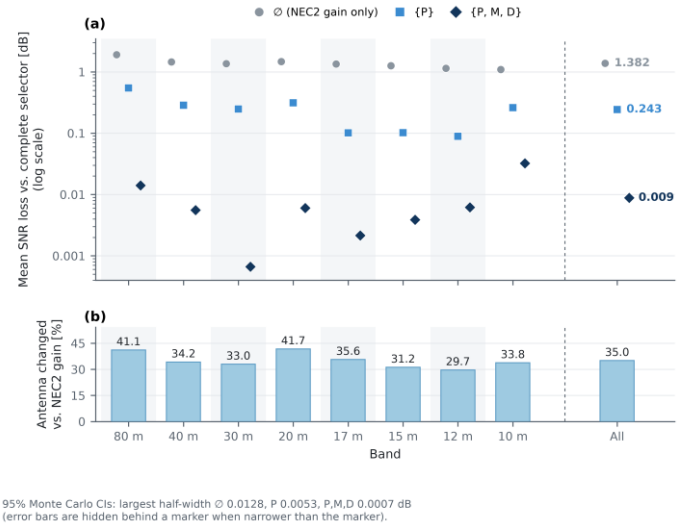
Rule	Dynamic gain vs. NEC2 (dB)	Dynamic loss vs. complete (dB)	Fixed gain vs. fixed NEC2 (dB)
Total gain only	0	1.382	0
P	1.138	0.2433	−0.1690
P,D	1.269	0.1130	−0.2906
P,M,D	1.373	0.0088	0.1305
P,M,D,R	1.382	≈ 0	0.1305
Complete	1.382	0	0.1305

Equal-weight averages over 24 cells; fixed results use independent test observations; values are rounded.

Polarization information alone provides 1.138 dB of the 1.382 dB dynamic improvement. Because {P} is equivalent to polarization-resolved NEC2 gain, the remaining 0.243 dB (17.6% of the full improvement over total gain) is the aggregate benefit of complete SNR modeling over that stronger baseline; adding D and M to P reduces the residual dynamic loss to 0.0088 dB. Fixed selection is less favorable for incomplete rules: P alone and P,D give negative incremental values under the adopted reference-value substitutions. Relative to the fixed P-informed rule, complete information improves fixed selection by $0.1305 - (-0.1690) = 0.2995$ dB.

C. *Frequency Dependence*

The mean dynamic loss of total-gain selection varies from 1.916 dB on 80 m to 1.096 dB on 10 m. Selection changes are most frequent on 20 m (41.7%) and 80 m (41.1%). Fig. 1 compares residual SNR losses and selection-change frequencies across the eight bands; the P,M,D rule has residual losses from about 0.001 dB on 30 m to 0.032 dB on 10 m.



95% Monte Carlo CIs: largest half-width ∅ 0.0128, P 0.0053, P,M,D 0.0007 dB
(error bars are hidden behind a marker when narrower than the marker).

Fig. 1. Dynamic antenna-selection performance across HF bands. (a) Mean SNR loss relative to the complete selector (logarithmic scale) for total NEC2 gain only (∅), rule {P}, and rule {P,M,D}; the rightmost group gives the equal-weight average over all bands. The 95% Monte Carlo confidence intervals are narrower than the markers (half-width of 0.012 dB or less). (b) Percentage of realizations in which the complete selector chooses a different antenna from the NEC2-gain baseline. Results are equally weighted across noise scenarios.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

D. Shapley Attribution

TABLE III. EXACT FIVE-CATEGORY SHAPLEY CONTRIBUTIONS TO INCREMENTAL SNR

Category	Dynamic (dB)	Dynamic share (%)	Fixed (dB)
Polarization (P)	1.153	83.4	−0.0706
Efficiency (E)	0.0081	0.6	−0.0612
Matching (M)	0.0852	6.2	0.2311
Noise coupling (D)	0.1311	9.5	0.0311
Receiver (R)	0.0045	0.3	≈ 0
Total	1.382	100.0	0.1305

Rounded contributions may differ slightly from the displayed totals.

Under dynamic selection, polarization accounts for 83.4% of incremental value, followed by noise coupling (9.5%) and impedance matching (6.2%). Fixed selection gives a different attribution: matching has the largest positive contribution, while polarization and efficiency contribute negatively under the adopted decision rules (Fig. 2).

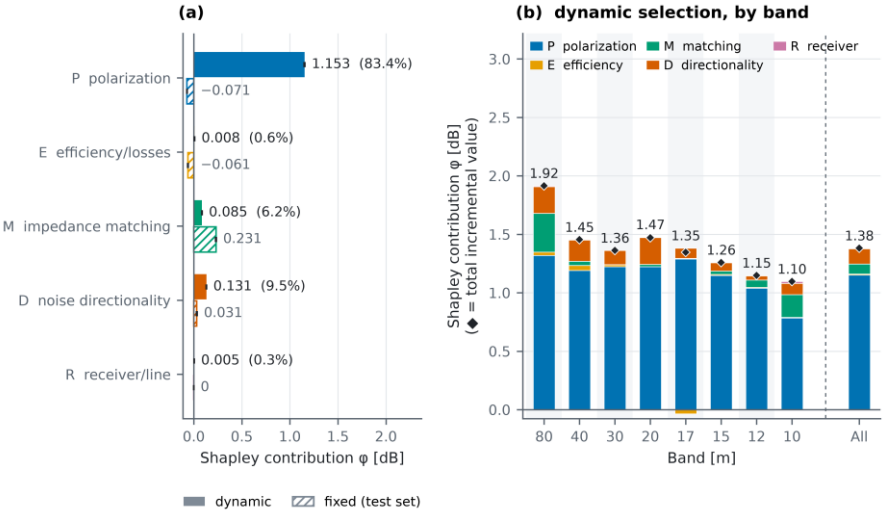


Fig. 2. Shapley attribution of incremental SNR value. (a) Study-level contributions of polarization (P), efficiency (E), matching (M), noise coupling (D), and receiver characteristics (R) under dynamic (solid) and fixed (hatched) selection, with 95% confidence intervals; negative contributions are retained. (b) Dynamic contributions by HF band, with the total incremental value marked by diamonds. Values are conditional on the candidate antennas, the total-gain baseline, and the partial-information substitution policies.

Conditioning on polarization changes the picture (Table IV). Of the 0.243 dB that complete modeling adds to polarization-resolved gain under dynamic selection, noise coupling contributes 55.5%, matching 30.2%, efficiency 12.5%, and the receiver 1.7%. Under fixed selection, matching dominates the conditional game (0.2921 of 0.2995 dB). The small negative contribution of efficiency (−0.0165 dB) reflects the adopted decision rules, not a physical penalty of knowing the efficiency.

TABLE IV. SHAPLEY CONTRIBUTIONS CONDITIONAL ON POLARIZATION INFORMATION

Category	Dynamic (dB)	Dynamic share (%)	Fixed (dB)
Efficiency (E)	0.0304	12.5	−0.0165
Matching (M)	0.0735	30.2	0.2921
Noise coupling (D)	0.1351	55.5	0.0239
Receiver (R)	0.0042	1.7	0.0000
Total	0.2433	100.0	0.2995

Four-player game $v_P(T) = v(T \cup \{P\}) - v(\{P\})$; fixed values are relative to the fixed P-informed rule; rounded values may not sum exactly.

E. Fixed Selection and Sensitivity

The complete fixed selector changed the antenna choice in five of the 24 cells: 80 and 20 m under isotropic and directional atmospheric noise, and 17 m under directional artificial noise. Fig. 3 compares dynamic improvements, fixed improvements, and losses relative to the ideal dynamic selector.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

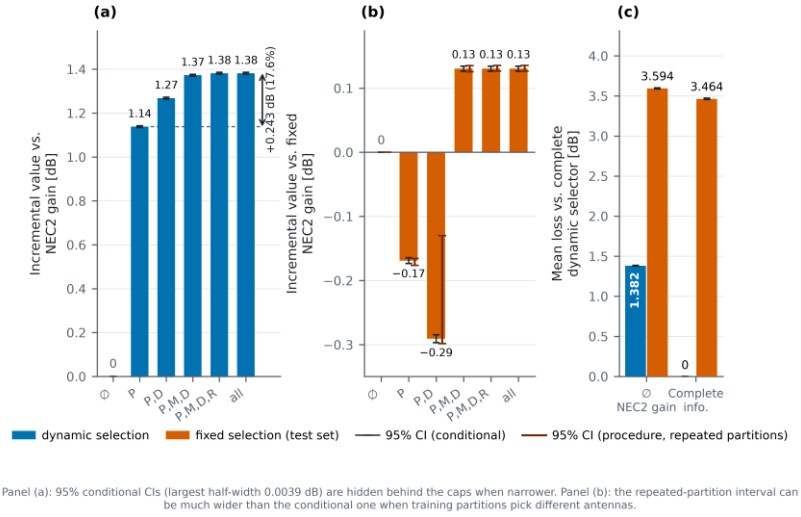


Fig. 3. Dynamic versus fixed antenna selection. (a) Incremental SNR improvement under dynamic selection for representative information rules; the arrow marks the benefit of the complete SNR model beyond polarization-resolved NEC2 gain, rule {P}. (b) Fixed-selection improvement relative to the fixed NEC2 baseline, with conditional (black) and repeated-partition (brown) 95% confidence intervals; the repeated-partition interval is wider when different training partitions select different antennas. (c) Mean loss of fixed NEC2 selection and of complete-information fixed selection relative to the complete dynamic selector, shown for dynamic (blue) and fixed (orange) policies. The conditional intervals in (a) and (c) are narrower than the markers. The two policies address different operational decisions.

Sensitivity analysis showed that changing the candidate antenna set has substantial effects: removing the vertical antenna reduced the total dynamic incremental value from 1.382 to 0.675 dB, and removing the Yagi reduced it to 0.949 dB. By noise scenario, the total dynamic value was 1.429 dB (isotropic), 1.306 dB (directional artificial), and 1.410 dB (directional atmospheric). For five of the eight bands the isotropic and directional atmospheric scenarios gave closely similar results, as follows from the construction of atm (directional only in the three lowest bands and at night); equal weighting therefore assigns repeated weight to effectively similar environments. These comparisons do not establish formal statistical equivalence.

IV. When Does SNR Modeling Pay Off?

A. Answer to the Central Question

Table V condenses the results into a decision guide. The value of going beyond NEC2 gain depends on two things: whether polarization is already resolved, and whether the antenna in use can change with conditions.

TABLE V. Decision Guide: When SNR Modeling Pays Off

Station situation	Recommended approach	Expected gain (dB)
One fixed antenna per band and noise scenario	Total NEC2 gain is adequate; the full SNR model adds little	0.1305 vs. fixed NEC2
Several antennas, ideal switching	Resolve polarization (polarization-resolved NEC2 gain)	1.138 vs. total gain
Same, plus full SNR model	Add noise coupling and impedance matching	0.243 beyond the row above
Choosing which antennas to build	The candidate set matters more than model detail	1.382 falls to 0.675 without the vertical
Quiet rural or low-noise site	Not evaluated; receiver noise and losses may matter	Not available

Dynamic values assume ideal switching; all values are simulated means conditional on the antennas and noise scenarios modeled, not guaranteed on-air improvements.

B. Why the Increments Are Small or Large

Selection by total directional NEC2 gain can differ substantially from selection by complete modeled SNR. However, most of the dynamic improvement arises when polarization is incorporated, and because NEC2 already provides horizontal and vertical components, this is not information unavailable from electromagnetic modeling. The appropriate comparison is thus among total-gain selection, polarization-informed selection, and complete SNR selection. Once polarization is known, most of the remaining 0.243 dB comes from how each antenna couples to external noise (55.5%) and from impedance matching (30.2%); in the five-category decomposition these appear small only because polarization absorbs most of the total.

Directional noise can change rankings because patterns collect different amounts of environmental noise; D also reflects differences between antenna-specific integrated coupling and a common reference, so it measures more than knowledge of the noise arrival direction. Efficiency and receiver characteristics have small dynamic contributions, consistent with externally noise-dominated reception, where signal attenuation is accompanied by similar attenuation of externally collected noise. The receiver contribution is also small by construction: receiver and line terms are common to all antennas, so R can change the ranking only when an antenna-specific term (E, M, or D) is also present in the denominator. This must not be generalized to quiet receiving sites, where receiver noise, efficiency, and losses could matter more. Matching remains relevant because impedance-dependent power transfer alters the balance between delivered signal and noise.

C. Fixed Versus Adaptive Operation

Dynamic selection assumes the best antenna can be chosen for every realization; fixed selection requires one antenna to serve the whole distribution of conditions. The fixed NEC2 selector loses 3.594 dB relative to the ideal dynamic selector, and complete-information fixed selection reduces this loss only to about 3.464 dB. For a station with one permanently installed antenna, refining the model therefore buys little; the larger prize

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

is the ability to switch among complementary antennas, together with the choice of which antennas to include (Section III-E). Exploiting that prize assumes information that may be hard to obtain, particularly the instantaneous signal polarization after ionospheric propagation. A practical system might instead measure SNR directly on the alternative antennas, which raises measurement uncertainty, switching delays, and propagation variability. The dynamic result is an ideal modeled benchmark, not a demonstrated operational improvement.

V. Limitations and Conclusions

The numerical results depend on four antenna geometries, eight frequencies, a single P.372 environment (residential), modeled noise angular distributions, and heuristic partial-information rules. The polarization model neglects coherent phase relationships; noise levels derive from statistical P.372-14 estimates, not site measurements, and updating to a later recommendation would require recalculation. Equal-weight aggregation does not reflect a measured distribution of real-world noise conditions. The most valuable extensions are explicit quiet-rural scenarios, alternative polarization distributions, confidence intervals for the conditional Shapley values, and experimental validation of the modeled rankings.

Under ideal dynamic selection, complete SNR information improved mean performance by 1.382 dB over total NEC2 gain and changed the antenna choice in about 35% of realizations, but 83.4% of the Shapley-attributed gain came from polarization, which NEC2 already supplies. Relative to polarization-resolved NEC2 gain, complete information added 0.243 dB, led by external-noise coupling (55.5%) and impedance matching (30.2%). For fixed selection, complete information improved performance by only 0.1305 dB, while fixed NEC2 selection stayed 3.594 dB below the ideal dynamic benchmark. SNR modeling therefore pays off mainly when polarization is resolved, when antennas can be switched, and when the candidate set is chosen with care; the quantitative results remain conditional on the simulated antennas, noise assumptions, and decision rules, pending experimental validation.

Data Availability

The data supporting this study, namely the executed NEC2 models, the SNR model and its assumptions file, the Monte Carlo and selection-rule code, the cell-level results, and the SHA-256 integrity manifests, are available from the corresponding author on reasonable request. The master random seed is 20261117, and the settings listed in Table I and the appendix tables are sufficient to repeat the experiment. The conditional Shapley values in Table IV are computed from the 32 stored coalition values without new simulations.

Appendix

TABLE VI. Signal Elevation Ranges by Band

Band	Elevation (°)	Band	Elevation (°)
80 m	10–90	17 m	3–40
40 m	8–85	15 m	3–35
30 m	5–70	12 m	3–30
20 m	3–45	10 m	3–30

TABLE VII. Angular Noise Laws by Scenario

Scenario	Atmospheric (A)	Man-made (M)	Galactic (G)
iso	isotropic, $p_V = 0.5$	isotropic, $p_V = 0.5$	isotropic, $p_V = 0.5$
hor	isotropic, $p_V = 0.5$	$e^{-\mathrm{el}/d_0}$, $d_0 \in \{3, 5, 8, 12, 15\}°$, $p_V \sim$ U(0.6,1)	isotropic, $p_V = 0.5$
atm	$e^{-\mathrm{el}/d_0}$, $d_0 \in \{10, 15, 20\}°$, $p_V = 0.5$, azimuthal modulation $1 + A\cos(\varphi - \varphi_0)$, depth 5–10 dB; night only, bands ≤ 10.2 MHz	isotropic, $p_V = 0.5$	isotropic, $p_V = 0.5$

TABLE VIII. Reference Values Used When a Category Is Unavailable (Common to All Antennas)

Category	Reference value
P	$p_H = 0.5$ (unpolarized signal): $G_{\mathrm{co}} \to G_{\mathrm{tot}}/2$
E	$f_{\mathrm{str}} = f_{\mathrm{gnd}} = 0$ (no dissipative noise); external coupling 1 (or η_{sky} if E is known and D is not)
M	$\tau = 1$ (ideal match)
D	median P.372 levels of the context ($z = 0$); common coupling 1
R	NF = 12 dB, $L = 1$ dB

References

[1] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken, NJ, USA: Wiley, 2016.

[2] G. J. Burke and A. J. Poggio, "Numerical Electromagnetics Code (NEC)—Method of moments," Lawrence Livermore Laboratory, Livermore, CA, USA, Rep. UCID-18834, 1981.

[3] *Radio Noise*, Recommendation ITU-R P.372-14, International Telecommunication Union, Geneva, Switzerland, 2019.

[4] C. J. Coleman, "A direction-sensitive model of atmospheric noise and its application to the analysis of HF receiving antennas," *Radio Sci.*, vol. 37, no. 3, 2002, doi: 10.1029/2000RS002567.

[5] C. J. Coleman, "Noise and the choice of antenna in HF communications," in *Proc. 10th IET Int. Conf. Ionospheric Radio Systems and Techniques*, 2006, pp. 321–325, doi: 10.1049/cp:20060294.

[6] S. R. Best, "Realized noise figure of the general receiving antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 702–705, 2013, doi: 10.1109/LAWP.2013.2264593.

[7] D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ, USA: Wiley, 2012.

[8] H. T. Friis, "Noise figures of radio receivers," *Proc. IRE*, vol. 32, no. 7, pp. 419–422, Jul. 1944, doi: 10.1109/JRPROC.1944.232049.

[9] L. S. Shapley, "A value for n-person games," in *Contributions to the Theory of Games, Vol. II*, H. W. Kuhn and A. W. Tucker, Eds. Princeton, NJ, USA: Princeton Univ. Press, 1953, pp. 307–317.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)