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A Geometry-Gated Coordination of Reconfigurable Intelligent Surfaces for Maritime Surveillance Communications

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Abstract

Maritime surveillance communications operate across moving vessels, low-power buoys, coastal gateways, and aerial platforms while the sea surface changes the propagation geometry. This paper develops MARISCA, a geometry-gated coordination architecture for Reconfigurable Intelligent Surfaces (RISs) carried by buoys, vessels, Unmanned Aerial Vehicles (UAV), or fixed offshore infrastructure. The central design principle is that a reflected route is admissible only while both radio legs, platform pose, channel-state age, control reliability, and energy constraints are jointly valid. The paper separates three objects that are frequently conflated: The physical RIS-assisted sublink, the network controller that selects among deployment layers, and the evidence required to justify a surveillance-level claim. A narrowband model defines the direct and cascaded channels, phase quantization, imperfect channel information, and control-cycle timing. A controller specification then performs viability screening before optimization and retains a verified incumbent route when a new configuration cannot be completed inside the usable channel-state window. The literature synthesis connects maritime propagation, UAV networking, RIS channel estimation, hardware limits, and multi-RIS control. A matched-scenario evaluation protocol defines baselines, ablations, link and system metrics, energy boundaries, and failure tests. MARISCA remains a proposed architecture: No simulation or field advantage is claimed. Its contribution is a falsifiable path from maritime geometry to safe surface selection and from link improvement to mission-relevant evidence.

Keywords: Maritime communications, Reconfigurable intelligent surface, Offshore surveillance, Unmanned aerial vehicles-assisted networks, Channel-state information, Geometry-aware control, Reproducible evaluation.

1 | Introduction

Maritime surveillance links must serve heterogeneous endpoints over a medium that is neither static nor uniformly terrestrial. Coastal stations communicate with vessels and low-profile sensor gateways; Unmanned Aerial Vehicles (UAVs) may extend visibility; satellite and terrestrial systems provide complementary

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coverage. Distance, sea-surface reflection, evaporation ducts, antenna height, platform motion, weather, blockage, and sparse scattering can all change the usable channel [1–4]. The engineering problem is therefore not merely to create a stronger reflected signal. It is to decide whether a particular reflected path is physically viable, whether it can be configured before the channel state becomes stale, and whether its cost is justified for the surveillance service.

Reconfigurable Intelligent Surfaces (RISs) reshape an incident wave through electronically controlled elements. Foundational work positioned RISs as a means to program the propagation environment rather than only the transmitter and receiver [5–10]. That promise is conditional. An RIS is normally passive or nearly passive; it neither regenerates the signal like a decode-and-forward relay nor removes the two-leg path loss. Its gain depends on aperture, element response, geometry, phase accuracy, channel estimation, control latency, and hardware losses [11–17]. Mobility makes these dependencies more severe because the configuration must remain aligned with the current path.

Recent studies have already connected RISs with maritime links, UAV placement, jamming resistance, offshore infrastructure, and wave-dependent channels [18–21]. Accordingly, novelty cannot rest on the phrase "RIS at sea". The unresolved architectural question is how heterogeneous candidate surfaces should be screened, selected, configured, verified, and abandoned when conditions change. MARISCA addresses that question by introducing geometry-gated coordination: Optimization is attempted only after a candidate passes a joint viability gate, and actuation is accepted only if the predicted configuration remains valid within the control cycle.

The paper makes four contributions: 1) it defines an architecture that separates payload, observation, optimization, and actuation rather than treating a network diagram as a radio route. 2) it gives a bounded physical model that distinguishes the direct channel from a cascaded RIS channel under phase quantization and imperfect information. 3) it specifies a deadline-aware controller with explicit fallback. 4) it develops an evidence hierarchy and matched-scenario protocol for determining whether link-level improvement becomes system- and mission-level value. The work is a design and validation framework, not an experimental performance report.

2|Literature and the Maritime Control Gap

2.1|Maritime Propagation and Network Alternatives

Maritime-communication surveys described a heterogeneous ecosystem of coastal, aerial, satellite, and vessel networks, with coverage and resource-management constraints that vary by service [1], [2]. Channel surveys distinguished near-sea-surface links from air-to-sea links and emphasized location dependence, sparse scattering, two-ray behavior, ducting, and measurement scarcity [3], [4]. Measured ship-to-ship work further showed that model parameters depend on the specific waterway, antenna configuration, frequency, and environment [22]. These findings rule out a universal "maritime channel" and motivate scenario-indexed models.

Maritime Internet of Things (IoT) and observatory studies shifted attention from peak data rate to telemetry continuity, low-power access, and mixed sensing infrastructures [23–25]. Autonomous surveillance platforms added onboard perception and cloud interaction [26]. Such systems establish the workload context for MARISCA, but they are not physical-layer RIS baselines. A detector accuracy, observatory uptime, or image dataset cannot substitute for radio-channel realizations, packet timestamps, or controller energy.

2.2|Reconfigurable Intelligent Surfaces Physics, Modeling, and Practical Control

RIS research moved from the smart-radio-environment concept toward increasingly physical communication models [5–10]. Joint active and passive beamforming formulations showed how surface phases can be optimized together with the transmitter [11]. Energy-efficiency analyses quantified the potential of nearly

passive apertures [12], while comparisons with relaying clarified that an RIS does not decode, amplify, or regenerate a signal [13]. Experimental path-loss studies and electromagnetic treatments demonstrated that surface size, distance, incidence, reradiation, and near-/far-field assumptions determine scaling [14–16]. These results support a crucial constraint for maritime deployment: a surface cannot be selected from map proximity alone.

Channel acquisition is a second bottleneck. Passive elements cannot independently transmit pilots, so cascaded channels must be inferred through controlled patterns and observations at active nodes. Surveys and general frameworks examined identifiability, pilot overhead, sparsity, correlation, wideband operation, and practical beamforming [17], [27–29]. Phase quantization, estimation error, coupling, and hardware losses can erode the coherent sum that ideal models predict [14–17], [30]. For mobile vessels and UAVs, the relevant question is not only estimation accuracy but whether estimation, optimization, command delivery, and settling finish before the usable state expires.

2.3 | Unmanned Aerial Vehicles and Multi-Platform Reconfigurable Intelligent Surfaces Coordination

UAV communication literature treated altitude, trajectory, air-to-ground propagation, payload, propulsion energy, and regulations as coupled design variables [31], [32]. Aerial RIS concepts added surface weight, orientation, channel acquisition, and beam alignment [33]. Maritime UAV surveys then placed those constraints within offshore coverage and backhaul conditions [2]. Yang et al. [18] jointly considered an energy-harvesting UAV-RIS, placement, phase control, and anti-jamming decisions; Zhang et al. [19] modeled a wave-aware RIS on fixed offshore infrastructure. These studies are direct predecessors, but they optimize particular deployments. MARISCA instead formalizes the admission and switching logic among buoy, vessel, aerial, fixed, and direct alternatives.

2.4 | The Unresolved Gap

The literature left three levels weakly connected. Physical-layer studies optimized a specified cascaded channel; deployment studies selected locations under assumed state information; maritime applications required coverage continuity under mobility and resource constraints. A credible architecture must connect them without allowing evidence to jump levels. MARISCA therefore uses three linked contracts: a path-validity contract for the radio geometry, a control-cycle contract for state freshness and actuation, and an evidence contract that separates link, system, and mission claims.

Table 1. Literature streams and the specific gap addressed by MARISCA.

Stream	Established Contribution	Residual Maritime Risk	MARISCA Response
Maritime channels [1–4], [22]	Measured and analytical models for near-sea and air-to-sea links	A model may be transferred outside its frequency, geometry, or sea state	Bind every result to a declared scenario and calibrated model
RIS physics [5–16]	Programmable reflection, beamforming, path-loss and energy analysis	Ideal phase coherence can hide two-leg loss and hardware limits	Screen both legs and account for aperture, loss, and quantization
Channel State Information (CSI) and control [17], [27–30]	Channel estimation and practical passive beamforming	Pilot and computation time may exceed state validity	Close observation, optimization, command, and verification inside one window
UAV/maritime RIS [2], [18–21], [30–33]	Mobile or offshore surface placement and optimization	One selected platform does not solve multi-layer switching	Coordinate platform alternatives with fallback and hysteresis
Surveillance applications [23–26]	Operational sensing and autonomous observation contexts	Application outcomes are not radio evidence	Require a traceable chain from link to served mission traffic

3 | MARISCA Architecture

3.1 | Functional Planes

MARISCA contains four functional planes. The service plane declares traffic class, deadline, reliability target, and geographic demand. The observation plane acquires pilots, position, attitude, sea-state indicators, energy state, and control-link quality. The coordination plane screens candidate routes and optimizes only the surviving alternatives. The actuation plane sends surface and radio commands, verifies the result, and either activates the route or retains a safe incumbent. A fusion application may consume surveillance outputs, but it is outside the radio-performance claim unless implemented and measured.

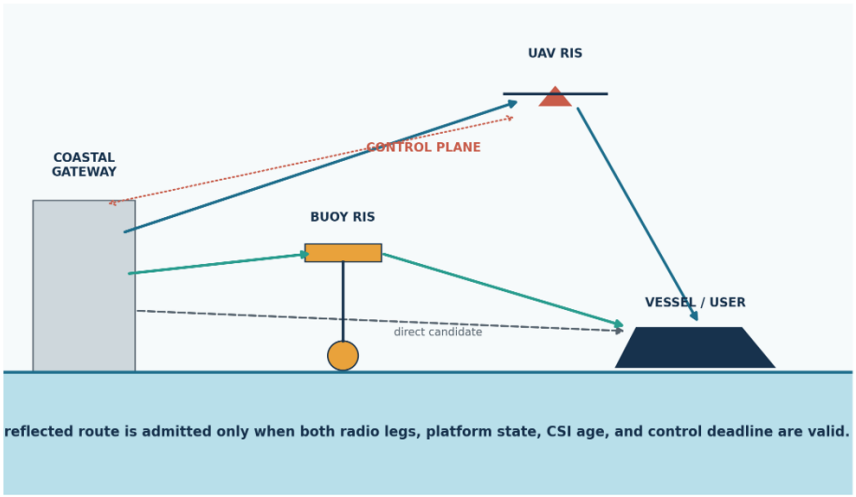


Fig. 1. Geometry-gated MARISCA topology.

The direct, buoy-RIS, and UAV-RIS routes are alternatives rather than an assumed chain.

A reflected route enters optimization only when both propagation legs, platform pose, channel-state age, command reliability, and energy constraints are simultaneously admissible.

3.2 | Candidate Path State

For candidate surface k at time t, define a state vector $z_k(t)$ containing transmitter-to-surface geometry, surface-to-receiver geometry, platform pose and uncertainty, channel estimates and their age, phase resolution, controller energy, command-link reliability, and regulatory availability. A binary gate $G_k(z_k)=1$ admits the path only if all mandatory constraints hold. The controller may use soft margins inside optimization, but it must not convert a failed safety, geometry, or control constraint into a merely penalized candidate. This distinction prevents a mathematically attractive but physically unavailable route from winning the objective.

3.3 | Information and Failure Semantics

Payload and control paths are explicitly separated. Payload packets follow the activated radio route. Observation reports and surface commands follow named control links with their own delays and loss probabilities. If observations are stale, optimization fails, a command acknowledgment is absent, or verification falls below its threshold, the controller returns to the incumbent route. Switching hysteresis is required so that small predicted gains do not cause repeated handovers. Every reported failure is classified as geometry, estimation, optimization, command, verification, energy, or service failure rather than being hidden inside average throughput.

4 | Physical and Control Model

4.1 | Single-Surface Sublink

Consider one narrowband single-antenna transmitter–receiver pair and one RIS with N elements. Let h_d be the direct complex channel, f_n the transmitter-to-element channel, g_n the element-to-receiver channel, ϱ_n the reflection amplitude, and θ_n the applied phase. The effective channel is $h_{eff} = h_d + \Sigma_{n=1}^{N} \varrho_n g_n f_n e^{\{j\theta_n\}}$. With transmit power P, bandwidth B, noise spectral density N_0, and compatible interference power I, Signal-to-Interference-plus-Noise Ratio (SINR) = $P|h_{eff}|^2/(N_0B+I)$. This expression defines the computational object but does not guarantee gain: the cascaded coefficients already contain the two propagation legs and surface losses.

If the hardware supports b-bit phase control, θ_n belongs to a finite codebook of 2^b values. Let the controller use estimates $\hat{f}_n$ and $\hat{g}_n$ with bounded or stochastic errors and a direct-channel estimate $\hat{h}_d$. The optimization should then report whether it maximizes estimated SINR, a robust lower quantile, outage probability, energy-normalized service, or another declared objective. A configuration optimized for an instantaneous estimate is not automatically robust to vessel motion or surface rotation.

4.2 | Multi-Platform Selection

Let K(t) be the candidates with $G_k=1$, augmented by the direct route k=0. The controller chooses a route and configuration that maximize a declared utility U_k while meeting service and resource constraints. U_k may combine predicted link quality, served traffic, handover cost, energy, and risk, but every term and scale must be disclosed. Multiple simultaneous RISs require a new channel model; MARISCA does not approximate a passive multi-bounce chain by adding independent single-RIS gains.

4.3 | Deadline-Aware Cycle

Let T_{obs}, T_{gate}, T_{opt}, T_{cmd}, and T_{set} denote observation, screening, optimization, command, and hardware-settling time. Let T_{valid} be the usable lifetime of the combined geometry and channel state after uncertainty margins. A configuration is actionable only if $T_{obs}+T_{gate}+T_{opt}+T_{cmd}+T_{set} < T_{valid}$. Verification and payload switching must also meet the service deadline. This inequality is the control boundary of the proposal: An excellent phase solution delivered after state expiry is not a successful decision.

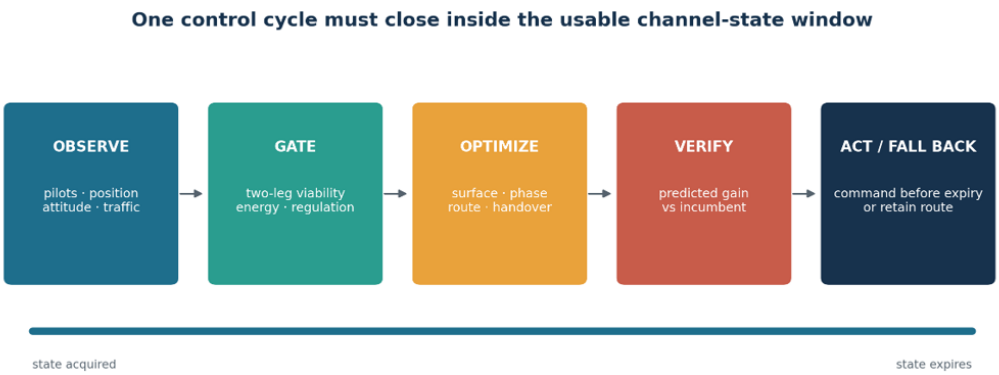


Fig. 2. Deadline-aware MARISCA control cycle.

The sequence is not a generic processing pipeline: Every stage consumes the same finite channel-state window. If the cycle cannot close before expiry, the architecture retains the incumbent route rather than actuating a stale optimum.

Table 2. Minimum state and failure record for each candidate route.

Object	Minimum Fields	Failure Test	Fallback Implication
Geometry	Coordinates, heights, orientation, uncertainty, visibility	Either radio leg blocked or outside surface field of view	Reject candidate
Channel state	Direct/cascaded estimates, timestamp, error model, coherence proxy	Age or uncertainty exceeds declared bound	Re-estimate or retain incumbent
Surface	Aperture, elements, amplitude loss, phase codebook, settling time	Command unavailable or configuration cannot settle in time	Disable surface layer
Platform	Energy, attitude, trajectory, payload and regulatory state	Endurance or operating constraint violated	Use another platform class
Service	Traffic, reliability, latency, priority and handover state	Predicted route misses required service envelope	Preserve feasible route or shed traffic explicitly

5 | Controller Specification

5.1 | Observation and Screening

At each decision epoch, the controller freezes a timestamped observation bundle. It rejects candidates with missing or incompatible units, failed geometry, insufficient control reliability, depleted energy, or invalid operating status. Surviving candidates receive uncertainty margins derived from pose and channel errors. Screening is deterministic for mandatory constraints so that later optimization cannot conceal infeasibility.

5.2 | Optimization and Incumbent Comparison

For each admitted candidate, the controller computes a configuration under a common time budget. Exact, alternating, heuristic, or learning-based solvers may be used, but their input, stopping rule, warm start, and failure status must be recorded [34]. The best candidate is compared with the current route using a switching threshold that includes handover cost and prediction uncertainty. A new route is commanded only when its conservative value exceeds the incumbent by the declared margin.

5.3 | Verification and Safe Degradation

After actuation, a short verification measurement tests whether received quality and command status agree with the predicted envelope. Failed verification triggers rollback. When no reflected route is admissible, MARISCA does not manufacture connectivity; it continues the direct, relay, aerial, or satellite alternative supplied by the surrounding network, or declares service degradation. The architecture therefore coordinates options but does not replace the need for redundant maritime communications.

Table 3. Controller outputs required for audit and reproduction.

Stage	Recorded Output	Why It Matters
Observe	Timestamped geometry, pose, pilots, uncertainty, traffic and energy	Reconstructs the information actually available to the decision
Gate	Candidate-by-constraint pass/fail matrix	Distinguishes physical infeasibility from poor optimization
Optimize	Objective, configuration, predicted interval, runtime and status	Makes solver comparison and stale-solution detection possible
Decide	Incumbent, challenger, switching margin and chosen action	Exposes hysteresis and handover logic
Verify	Post-command measurement, acknowledgment and rollback status	Prevents predicted gain from being reported as delivered service

6 | Evaluation Architecture

6.1 | Scenarios and Baselines

An evaluation should publish coordinates and trajectories; antenna height, pattern, polarization, carrier, bandwidth, transmit power, noise and interference assumptions; surface aperture, element count, loss, phase resolution and mounting; sea state, weather and duct assumptions; traffic traces; pilot schedule; and computation hardware. The same channel realizations and mobility sequence must be used for all methods. At minimum, compare the direct coastal link, a matched active relay or UAV link where feasible, fixed-phase RIS, channel-aware single-RIS, oracle platform selection with perfect state information, and MARISCA with realistic estimation and control overhead.

Ablations should remove the viability gate, uncertainty margin, switching hysteresis, each platform class, and verification/rollback in turn. These experiments answer different questions. Removing the gate measures the damage caused by optimizing unavailable routes; removing hysteresis tests instability; removing verification tests whether predicted improvement survives actuation. Tuning data and final test scenarios must be separated if learning or automatic configuration is used.

6.2 | Metrics and Evidence Levels

Link evidence includes received SINR or Signal-to-Noise Ratio (SNR), outage at a declared threshold, channel-estimation error, and the fraction of physically viable reflected paths. System evidence includes deadline-feasible packet delivery, control overhead, route-switch rate, tail latency, controller failure, and served traffic. Mission evidence includes surveillance-region service, energy endurance, recovery time, and the fraction of priority observations delivered within their deadline. SNR in dB is a level; gain in dB is a matched difference. Coverage area is not radial range, and predicted utility is not delivered service.

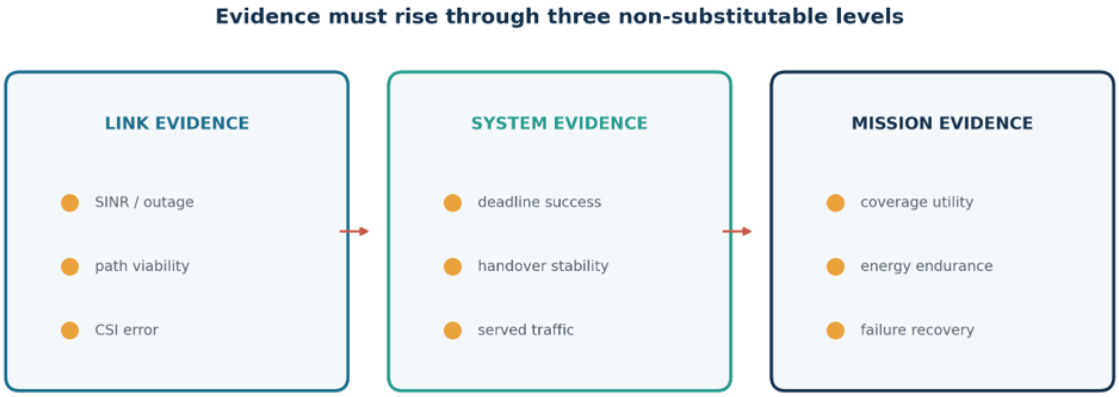


Fig. 3. MARISCA evidence hierarchy.

Link, system, and mission evidence answer different questions and cannot substitute for one another. A link-level SINR improvement supports a surveillance claim only after deadline, traffic, energy, and recovery behavior have also been traced.

Table 4. Operational metric definitions for matched-scenario evaluation.

Measure	Operational Definition	Required Evidence
Path viability	Fraction of epochs in which every mandatory gate for a named route passes	Candidate-by-constraint matrix and timestamps
Outage	Fraction of independent samples or packets below a declared service threshold	Threshold, sampling unit, run count and uncertainty interval
Deadline-feasible delivery	Fraction of generated priority packets delivered before their individual deadline	Packet timestamps, losses, retransmissions and route state
Control-cycle success	Fraction of decisions observed, solved, commanded and settled before T_valid	Per-stage timing and expiry rule
Energy endurance	Served mission time under a declared boundary including propulsion, radio, controller and surface	Power traces, operating modes, failures and residual energy
Recovery time	Elapsed time from disruption detection to restored declared service	Event log, fallback action and post-event service trace

6.3 | Statistical Reporting and Reproducibility

Report run-level outcomes, medians and relevant quantiles, confidence intervals, and failure counts rather than only favorable averages. Pair methods on identical scenarios and random seeds. When several methods are compared across scenario families, use an omnibus paired procedure and corrected post-hoc comparisons, while also reporting effect sizes and operational margins [35–37]. Statistical significance cannot repair an invalid channel model or unequal resource boundary.

The reproducibility package should contain the scenario manifest, propagation and hardware parameters, raw channel or packet traces, random seeds, feasibility checker, controller configuration, software versions, and scripts for all tables and figures. Scene imagery can provide vessel positions or demand regions only when its dataset, version, license, preprocessing, and mapping are documented; it does not supply radio CSI, noise, or outage observations.

7 | Security, Safety, and Deployment Boundaries

Control integrity is a prerequisite because false position, stale CSI, spoofed platform status, or altered phase commands can redirect or disable a route. The threat model should distinguish passive eavesdropping, pilot contamination, jamming, command injection, Global Navigation Satellite System (GNSS)/Automatic Identification System (AIS) manipulation, and compromise of the coordination service [38]. Physical-layer security studies may motivate robust objectives, but they do not replace authentication, authorization, key management, command freshness, and audit logs.

Operational deployment also requires electromagnetic compliance, UAV flight permission, vessel cooperation, weather limits, saltwater durability, mechanical stabilization, maintenance access, and failure-safe behavior. A passive surface still consumes controller and switching energy and may impose significant support-platform energy. MARISCA treats these as gating variables rather than as future details outside the model.

8 | Limitations and Research Agenda

MARISCA is not yet an implemented optimizer, simulator, prototype, or field system. The narrowband equation is an interpretive sublink model; wideband, multi-antenna, near-field, multi-RIS, and multiuser operation require explicit extensions. No numerical improvement in coverage, outage, latency, or energy is established here. The architecture also assumes that a surrounding network provides at least one incumbent or fallback option; it cannot create service when every physical path is unavailable.

Four studies would provide the strongest next evidence: 1) a controlled simulator should compare direct, active-relay, fixed-RIS, single-RIS, oracle, and MARISCA decisions on identical maritime trajectories, 2) a hardware-in-the-loop experiment should measure pose error, phase settling, command loss, and stale-state failure, 3) a coastal field trial should test at least one moving vessel and one mounted surface with synchronized RF, weather, and motion logs, and 4) a security campaign should inject pilot, position, and command faults and measure detection, rollback, and service recovery. Each stage should preserve the same evidence hierarchy so that a stronger experiment extends rather than replaces the previous record.

9 | Conclusion

MARISCA reframes maritime RIS coordination as a validity problem before it becomes an optimization problem. A buoy-, vessel-, UAV-, or infrastructure-mounted surface is considered only while both propagation legs, platform state, channel information, control path, energy, and operating authority remain jointly valid. The controller then closes observation, screening, optimization, actuation, and verification inside the usable state window, with explicit fallback when it cannot. This geometry-gated architecture separates a physical reflected link from network control and separates link improvement from surveillance value. Its scientific status is deliberately bounded: it is a reproducible design hypothesis. The proposed evaluation plan provides the path by which that hypothesis can be rejected, refined, or supported through matched simulation, hardware-in-the-loop tests, and field evidence.

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Author Contributions

Habibeh Karimi: Conceptualization, methodology, and writing—original draft. Khatereh Bagherzadeh Asl: Technical analysis, literature review, and validation framework. Samira Torabi: Supervision, critical review, and writing—review and editing. All authors reviewed and approved the final manuscript.

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Data Availability

No new datasets were generated or analyzed in this study. All supporting information is derived from previously published literature cited in the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the research or publication of this article.

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