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A Comprehensive Review of the Architecture, Challenges, Key Technologies, and Future Trends in Space–Air–Ground–Ocean Integrated Networks

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ABSTRACT
Space–Air–Ground–Ocean Integrated Networks are being investigated as a communication framework for exchanging data across terrestrial, aerial, space, maritime-surface, and underwater environments. Environmental monitoring and resilient operation along strategic waterways expose limitations in conventional single-domain architectures, particularly when links differ sharply in propagation, capacity, delay, availability, and security exposure. This review assesses emerging communication infrastructures across the four domains and examines signal attenuation underwater, satellite-link delay, channel uncertainty, intelligent surface gateways, heterogeneous radio-frequency (RF), acoustic, and optical media, software-defined networking (SDN), network function virtualization (NFV), and adaptive protocols. Building on prior surveys of individual domains or themes, it jointly analyzes cross-domain architecture, heterogeneous transmission media, protocol convergence through intelligent surface gateways, SDN/NFV- and artificial intelligence (AI)-assisted network management, cyber resilience, and open research directions for strategically important maritime environments. The review concludes by identifying evidence gaps and validation priorities for interoperable, energy-aware, secure, and disruption-tolerant services spanning remote ocean regions and other heterogeneous environments.

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Keywords
Integrated Networks, Intelligent Technologies, Cyber Resilience, Heterogeneous Environments, Underwater Communications, Low-Earth-Orbit Satellites.

1. INTRODUCTION

The accelerating expansion of telecommunication infrastructure has transformed both human interaction and machine-to-machine (M2M) communication. Investment, standardization, and deployment have nevertheless remained concentrated in terrestrial cellular and fiber systems. Although these infrastructures provide mature high-capacity service in populated areas, their cost and dependence on fixed sites leave persistent coverage and service-continuity gaps across oceans, polar regions, mountainous terrain, and remote airspace [1], [2]. These limitations motivate architectures that extend connectivity through space, aerial, maritime-surface, and underwater domains.

The integration of terrestrial, aerial, space, maritime-surface, and underwater systems is intended to extend service availability across heterogeneous environments. Rather than forming a fully transparent or universally reliable infrastructure, the resulting architecture must coordinate domains with different propagation, mobility, capacity, energy, and trust constraints [1], [2], [3], [4]. Its design objectives include improved coverage continuity, manageable quality of service, and resilience, while the degree to which these objectives can be met remains scenario-dependent.

Cross-domain integration is motivated by global sensing and communication applications, including environmental observation, maritime navigation support, disaster response, remote-area connectivity, and security monitoring [1], [2], [3], [5]. These applications have different timeliness and reliability requirements; they do not all imply a continuously available data stream. Their implementation requires coordination among satellite, aerial, terrestrial, and underwater systems through routing, resource management, and gateway adaptation.

The Historical Isolation of Conventional Networks and a Physical Analysis of Their Limitations

Historically separate space, terrestrial, and underwater networks use different physical layers, delays, mobility assumptions, and protocol stacks, so direct interoperability cannot be inferred from connectivity alone [1], [2], [6], [7], [8]. Satellite links contribute wide-area reach but introduce orbit-dependent delay and topology variation [1], [9], whereas underwater links trade acoustic reach against high delay and use optical links for shorter high-rate transfer [7], [8]. Sections 2 and 3 analyze these architectural and physical asymmetries; the integration problem is to expose them to routing and gateway control rather than repeat terrestrial assumptions.

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6G Architecture and the Convergence of Enabling Technologies

Sixth-generation research brings satellite, aerial, terrestrial, and maritime resources into a common design space, but coverage, latency, energy, and resilience targets remain scenario-dependent [1], [2], [10]. Low-power processing and harvesting, mobile relays, autonomous underwater vehicles (AUVs), and multimodal gateways expand the design space without removing propagation, maintenance, and contact constraints [11], [7], [5], [12]. Accordingly, Sections 2–5 evaluate these technologies as conditional components of an integrated architecture rather than as independent solutions.

Cyber Resilience and Connectivity at the Strait of Hormuz

For strategic maritime environments such as the Strait of Hormuz, the benefit of integration is path and sensing diversity, while the cost is a larger cross-domain trust and attack surface [3], [13]. Alternative routing is available only when topology, capacity, credentials, contacts, and gateway resources permit; continuity is therefore an engineering objective rather than a guaranteed outcome. Section 5.4 examines the resulting need for authenticated, disruption-tolerant control and detection across heterogeneous links.

The Necessity of Engineering Transport-Layer Protocols and the Challenge of Medium Translation

Cross-domain transport must distinguish congestion from channel loss, disruption, and long acoustic delay. Delay-tolerant networking (DTN) using Bundle Protocol Version 7 (BPv7) can provide persistent store-and-forward operation, while surface gateways buffer, translate, aggregate, and schedule traffic between underwater and above-water links [8], [14], [5]. These mechanisms shift rather than eliminate constraints: storage, expiry, energy, security, and contact scheduling become coupled design variables, analyzed in Section 4.

Edge Processing, Artificial Intelligence, and the Outlook for Autonomous Resource Management

Software-defined networking (SDN), network function virtualization (NFV), edge computing, and artificial intelligence (AI) can coordinate selected routing and resource-management tasks, but their value depends on controller reachability, trustworthy telemetry, compute capacity, model validity, and safe fallback behavior [15], [16], [17], [18]. Section 5 therefore treats automation as a closed-loop control problem whose gains and failure modes must be evaluated together, rather than as an automatic source of optimality.

Related Surveys and Contributions of This Review

Several influential surveys provide complementary foundations for this review. Liu et al. [1] examined space–air–ground integration, with emphasis on system integration, protocol optimization, and resource allocation. Zhu and Jiang [2] reviewed satellite–terrestrial architectures, applications, and challenges toward 6G. Within the underwater domain, Luo et al. [19] classified routing protocols for underwater wireless sensor networks, whereas Zeng et al. [7] reviewed underwater optical wireless communications. Afolabi et al. [16] surveyed network slicing and softwarization, and Shen et al. [18] examined next-generation computing technologies in space–air–ground integrated networks. Nguyen et al. [20] addressed prospective 6G security and privacy technologies, Guo et al. [3] focused on security in space–air–ground–sea integrated networks (SAGSINs), and Meng et al. [4] surveyed semantic communications for SAGSINs. To align with established four-domain terminology, this article uses SAGSIN [3], [4] as the abbreviation for the integrated space–air–ground–marine domain; the word “ocean” remains in the title to reflect the review's coverage of both surface and underwater environments.

Table 1 compares the declared scope and primary emphasis of these closely related surveys. The two four-domain surveys in the comparison emphasize security [3] and semantic communications [4], respectively. The remaining works declare three-domain, two-domain, or single-domain scopes, or address broader 6G security and terrestrial softwarization themes. The present review differs by organizing, in one article, four-domain architecture; radio, acoustic, and optical media; protocol convergence through surface gateways; SDN/NFV- and AI-based management; and cyber resilience. This is a scope-based comparison: a topic described as not central is outside a survey's declared main emphasis, not necessarily absent from every section of that paper.

Table 1. Scope-based comparison of this review with closely related surveys. Entries summarize each survey's declared network scope and primary emphasis.

Survey / year	Declared network scope	Marine / underwater coverage	Primary emphasis reported by the authors	Scope relative to the present review
Liu et al. [1], 2018	Space–air–ground	Not in declared scope	System integration, protocol optimization, and resource allocation	Foundational three-domain perspective; the declared scope does not include a marine tier.
Zhu and Jiang [2], 2022	Satellite–terrestrial	Not in declared scope	Architectures, applications, and challenges toward 6G	Two-domain integration perspective rather than a four-domain architecture.
Luo et al. [19], 2021	Underwater sensor networks	Direct coverage	Taxonomy of underwater routing protocols	Detailed single-domain routing perspective rather than an end-to-end cross-domain integration review.
Nguyen et al. [20], 2021	General 6G systems	Contextual	Prospective security and privacy technologies and challenges	Broad security lens rather than a domain-by-domain integration review.
Afolabi et al. [16], 2018	Terrestrial 5G	Not in declared scope	Network slicing, softwarization, and orchestration	Management framework for terrestrial systems; cross-domain integration is not the declared focus.
Zeng et al. [7], 2017	Underwater optical links	Direct coverage	Channels, modulation, coding, and implementations	Detailed single-medium perspective rather than heterogeneous-media integration.
Guo et al. [3], 2022	Space–air–ground–sea	Direct coverage	Threats, attacks, and countermeasures	Closest four-domain security survey; architecture, media, and gateways are not its declared primary emphasis.
Shen et al. [18], 2023	Space–air–ground	Not in declared scope	Next-generation computing, use cases, initiatives, and challenges	Computing-centered three-domain perspective; no marine tier in the declared scope.
Meng et al. [4], 2025	Space–air–ground–sea	Direct coverage	Semantic-communication frameworks, metrics, and challenges	Four-domain semantic-communications perspective; protocol convergence is not the declared primary emphasis.
This review, 2026	Space, air, ground/coastal, ocean surface and underwater	Direct coverage	Architecture, media, gateways and protocols, SDN/NFV, AI management, and resilience	Integrated synthesis across four domains and the principal physical and network-management planes.

Contributions of This Review

The literature considered in this review was supplemented and updated through targeted searches of IEEE Xplore, the ACM Digital Library, Semantic Scholar, and OpenAlex, most recently in August 2026. Search terms covered the principal themes of this review, including space–air–ground and space–air–ground–sea integrated networks, underwater communications, delay-tolerant networking, SDN/NFV, AI-enabled resource management, and 6G security. Priority was given to peer-reviewed surveys, tutorials, and representative primary studies directly relevant to the core dimensions analyzed in this article.

The main contributions of this review are as follows:

1. It synthesizes a four-domain reference architecture for Space–Air–Ground–Ocean Integrated Networks and introduces an eight-dimensional taxonomy that links architecture, media, gateways, routing, programmable management, AI-enabled adaptation, cyber resilience, and future enablers to the manuscript's analytical sections (Table 2 and Sections 2–6).
2. It comparatively analyzes the heterogeneous radio, acoustic, and optical transmission media across the four domains, identifying the physical-layer constraints that any integration architecture must accommodate (Section 3).
3. It examines protocol convergence across incompatible protocol stacks, positioning intelligent surface gateways (buoys and vessels) as the water–air integration interface, and reviews delay-tolerant networking, cross-domain routing, translation, and synchronization mechanisms (Section 4).
4. It reviews SDN/NFV-based control architectures and AI-enabled approaches—including hierarchical controller placement, network slicing, deep reinforcement learning, and federated learning—for cross-domain resource management (Section 5).
5. It analyzes cyber resilience from the physical layer to the network-management layer, with an operational focus on strategic maritime chokepoints, and structures open research directions covering quantum key distribution, battery-free sensing, and semantic communications (Sections 3, 5, and 6).

Analytical Taxonomy of Cross-Domain Integration

Table 2 transforms the review's descriptive topics into an eight-dimensional analytical framework. The dimensions progress from where and through what connectivity occurs (architecture and media), to how continuity is achieved (gateway/protocol convergence and routing), how resources are governed (SDN/NFV and AI), how service is protected (cyber resilience), and how the system may evolve (future enablers). They are complementary, not mutually exclusive, because routing, management, and resilience cross physical domains. The final column maps each dimension to the article section and representative literature.

Table 2. Eight-dimensional analytical taxonomy of Space–Air–Ground–Ocean Integrated Networks. The dimensions connect representative mechanisms to their cross-domain role, principal research challenge, manuscript section, and representative literature.

Taxonomy dimension	Classes / mechanisms	Cross-domain role	Main integration challenge	Section / sources
Architecture and domains	Domains: space; air; ground/coast; ocean (surface and underwater). Interface: surface gateways	Organizes coverage, relay, core, and sensing across four domains; surface gateways bridge ocean and air/ground links.	Mobility, handover, intermittency, and administrative boundaries.	Sec. 2; [1], [2], [3]
Physical transmission media	RF / millimeter-wave; free-space optical; acoustic; underwater optical	Matches links to propagation environments and enables multimodal selection.	Incompatible channel dynamics, delay/loss, alignment, and environmental sensitivity.	Sec. 3; [21], [22], [8], [7]
Protocol convergence and gateways	Buoy/vessel gateways; buffering; translation; store-and-forward	Bridges underwater and air/space stacks at the water-air boundary.	Heterogeneous timing, frames, addressing, and error behavior.	Sec. 4; [5], [14], [19]
Routing and cross-domain transfer	Delay-tolerant/store-and-forward; geographic/depth routing; AI-assisted routing	Selects and reroutes multihop paths across changing domains.	Reachability-delay-energy-stability trade-offs under mobility and routing voids.	Sec. 4; [14], [19], [23], [6], [24]
SDN/NFV and resource management	Hierarchical/distributed control; slicing; virtual functions; orchestration	Coordinates shared communication and computing resources across layers.	Controller placement, delayed loops, isolation, and resource abstraction.	Sec. 5; [25], [16], [17]
AI-enabled management	Deep reinforcement learning; federated learning; predictive adaptation; closed-loop control	Learns scheduling, link-selection, allocation, and adaptation policies.	Observability, nonstationarity, overhead, convergence, and explainability.	Sec. 5; [15], [25], [23], [24], [17], [26]
Cyber resilience	Authentication/zero trust; intrusion detection; anti-jamming; secure routing; recovery	Protects identity, control, and data; sustains service through attack or failure.	Distributed attack surface, constrained nodes, and cross-domain trust.	Secs. 3.5, 5.4; [20], [27], [3]
Future enablers	Quantum key distribution; energy harvesting; battery-free sensing; semantics	Targets secure keys, longer-lived sensing, and efficient information exchange.	Cross-medium feasibility, maturity, standards, cost, and integration.	Sec. 6; [28], [11], [4]

Read vertically, Table 2 distinguishes connectivity, continuity, governance, protection, and evolution; read horizontally, each row couples mechanisms with an integration role and an unresolved challenge. This two-level organization provides the analytical spine for Sections 2–6, while cross-cutting dimensions are revisited where their functions intersect.

Organization of the Article

To connect the taxonomy to the detailed review, the remainder of the article progresses from architecture and physical media to protocol convergence, programmable management, cyber resilience, and future research.

Accordingly, Section 2 presents the four-domain reference architecture and its topology model. Section 3 compares radio, free-space optical, underwater acoustic, and underwater optical media and their physical constraints. Section 4 reviews protocol convergence, delay-tolerant networking, routing, queue management, synchronization, and surface gateways. Section 5 examines SDN/NFV-based management, AI-assisted resource allocation, and cyber resilience. Section 6 discusses research-stage directions in quantum key distribution, battery-free underwater sensing, and semantic communication. Section 7 concludes the review.

- **REFERENCE ARCHITECTURE AND LAYER DECOMPOSITION OF SPACE–AIR–GROUND–OCEAN INTEGRATED NETWORKS**

For analytical purposes, this review adopts a four-domain reference architecture comprising the space, aerial, terrestrial-coastal, and marine-subsurface layers [3], [4]. The decomposition is a conceptual model rather than a universally standardized architecture. It is used to organize differences in propagation, mobility, capacity, delay, energy, and gateway function and to support the discussion associated with Figure 1.

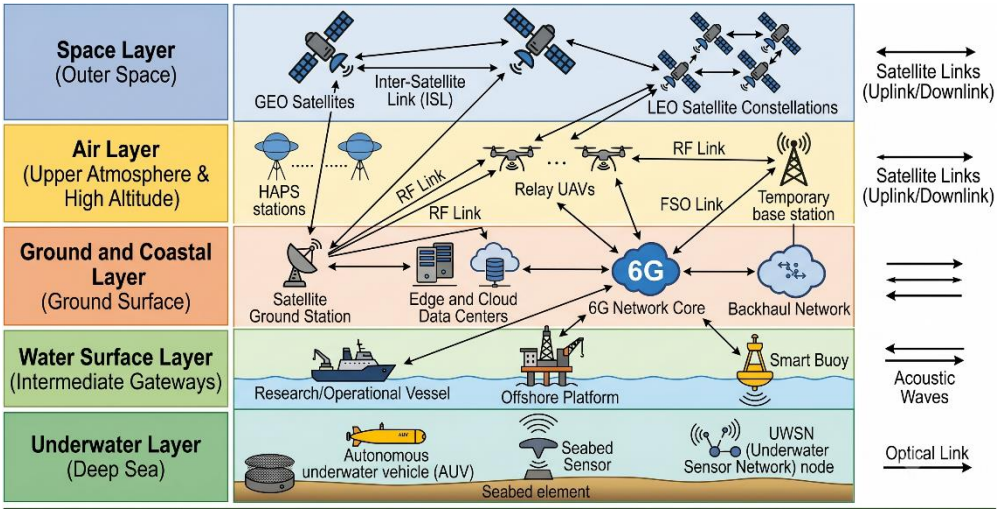


Figure 1. Reference architecture of Space–Air–Ground–Ocean Integrated Networks, showing the space, aerial, terrestrial/coastal, and ocean domains; the water-surface tier acts as an intermediate gateway within the ocean domain.

As shown in Figure 1, the communication layers—from space platforms to underwater nodes—can be interconnected through radio, acoustic, and optical links. This three-dimensional design can provide alternative paths around geographic or link-specific disruptions, but path availability and stability remain conditional on topology, propagation, energy, and gateway capabilities.

The Space Layer: Hybrid Satellite Constellations and Space Mesh Networks

The space layer supports wide-area coverage and connectivity between remote nodes and the network core. It may combine geostationary Earth orbit (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO) systems. GEO satellites orbit approximately 35,786 km above the equator and appear stationary to ground observers, which benefits persistent regional coverage but entails greater propagation delay than lower orbits. MEO lies between LEO and GEO and includes navigation and communication systems with intermediate coverage and delay characteristics [9].

LEO constellations operate below approximately 2,000 km and provide shorter propagation paths than GEO systems, while their high orbital motion creates frequent changes in visibility and topology [9]. Radio-frequency or optical inter-satellite links can form a dynamic space mesh, but link availability depends on constellation geometry, pointing, acquisition, tracking, spectrum, and terminal capability [1], [22]. Consequently, handover, routing, Doppler compensation, and adaptive coding must be designed for time-varying connectivity rather than assumed terrestrial-like delay.

2.2. The Aerial Layer: High-Altitude Platform Stations and Unmanned Aerial Vehicle Relay Networks

The aerial layer can bridge space systems and surface or maritime nodes through high-altitude platform stations (HAPS) and lower-altitude unmanned aerial vehicle (UAV) relays. The International Telecommunication Union (ITU) defines HAPS as radio stations on objects operating at 20–50 km altitude; some current development programs test quasi-stationary platforms around 20–25 km with intended endurance of several months [10]. Their coverage, capacity, and endurance depend on platform design, spectrum, payload, energy storage, weather, and deployment geometry, so these parameters should be evaluated for each scenario.

Lower-altitude UAV relays can provide rapidly deployable coverage and mobile edge processing, but their endurance and link quality are constrained by energy, payload, weather, interference, and flight regulation. Radio and free-space optical (FSO) links are both possible. For FSO, atmospheric turbulence and pointing error cause fading, and the selected statistical channel model must match the turbulence regime rather than being treated as universal [22].

2.3. The Terrestrial and Coastal Layer: The Network Core and Fiber-Optic-Connected Infrastructure

The terrestrial and coastal layer can host network-core functions, edge or cloud processing, satellite earth stations, cellular infrastructure, and fiber backhaul [1], [2], [18]. Depending on the deployment, coastal sites may also integrate radar, video sensing, maritime gateways, or cable landing facilities. These components aggregate traffic from selected aerial, space, surface, and underwater paths; their role and traffic volume depend on application scale, coverage, and available backhaul rather than making this layer universally the most vital or final hub.

Multi-access edge computing (MEC) can place selected processing functions nearer data sources or users, potentially reducing transport delay relative to remote-cloud processing [18]. Satellite earth stations and coastal gateways may connect space or maritime links to metropolitan fiber and other backhaul, while SDN-enabled functions can assist protocol adaptation [29]. Capacity planning must still account for bottlenecks, computation, storage, failure domains, and sensor population; MEC and high-capacity backhaul do not guarantee the lowest possible latency or bottleneck-free operation.

2.4. The Subsurface and Deep-Sea Layer: Wireless Sensor Networks and Autonomous Vehicles

The subsurface and deep-sea layer includes underwater sensor networks, autonomous underwater vehicles, anchored seabed nodes, and cabled assets. These systems support applications such as environmental sensing, seafloor observation, and vessel monitoring. Submerged nodes often depend on finite batteries, cabled supply, or locally available harvested energy; energy management can extend lifetime but cannot guarantee it [11], [12]. Maintenance accessibility, channel conditions, sensing duty cycle, and computation must therefore be included in deployment design.

Autonomous underwater vehicles can collect data from fixed sensors and act as mobile relays. Acoustic systems may use multicarrier techniques such as orthogonal frequency-division multiplexing (OFDM) together with Doppler estimation or compensation, but performance remains sensitive to motion, multipath, bandwidth, and channel coherence [6], [8]. For suitable short line-of-sight links, blue–green underwater optical wireless communication (UOWC) can provide much higher data rates, although absorption, scattering, turbidity, ambient light, and alignment constrain reliability [7]. Surface vessels and buoys then bridge underwater links to radio or optical upstream networks.

2.5. Topology Analysis and the Communication Model of Cross-Domain Nodes

Communication across the four domains can be represented as a time-varying graph whose nodes have markedly different mobility, energy, and link characteristics. Routing may therefore use predicted contact opportunities or positions, while gateways expose a consistent service to higher layers. In four-domain systems, mixed-integer optimization, graph algorithms, or learning-based methods may be selected according to the variables and constraints, with no single formulation mandatory for all deployments [1], [25], [23].

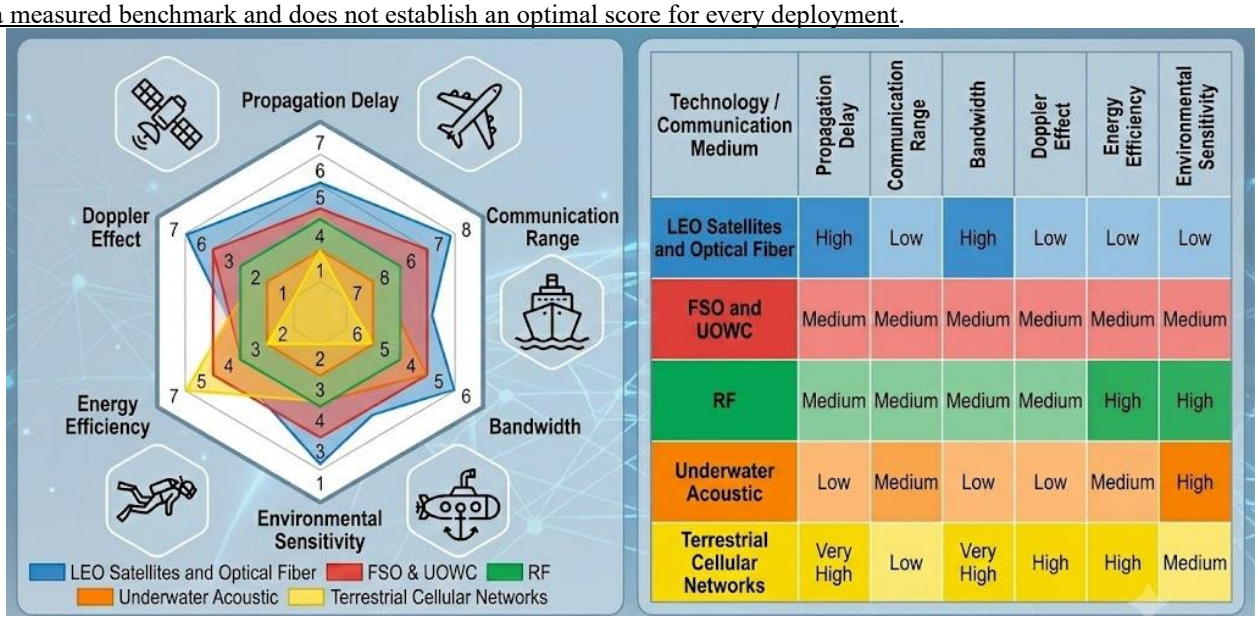
Cross-domain mobility may require handover or contact switching when a node leaves the coverage of a relay. Surface gateways can buffer traffic and translate between underwater acoustic or optical links and above-water radio or optical links [5]. Their adaptation speed is limited by measurement, computation, control-plane reachability, and link availability. Topology and resource management can use distributed optimization or edge intelligence, but no single method is the only feasible route to real-time operation [1], [29].

The architectural question is therefore where state, storage, computation, and trust should reside—not simply how many layers are drawn. Centralized coordination can simplify policy consistency but depends on long or intermittent control paths; domain controllers and surface gateways can react locally but introduce state-consistency, handover, and security-boundary problems [1], [3], [18], [5], [29]. This review therefore identifies a need for a reproducible four-domain evaluation framework that exposes competing architectures to common mobility, contact, energy, traffic, and attack conditions, supported by shared traces and interface definitions [3], [4].

PHYSICAL-MEDIA CHALLENGES AND HETEROGENEOUS COMMUNICATION TECHNOLOGIES

The design of cross-domain networks requires propagation models for space, aerial, surface, and underwater media. No single wireless medium satisfies every range, rate, delay, energy, and robustness requirement, so a deployment may combine radio, acoustic, and optical technologies [22], [7], [8]. Boundary effects, including refraction, reflection, absorption, turbulence, and interface loss, must be evaluated for the selected path. Figure 2 therefore provides a qualitative comparison to support scenario-specific media selection rather than identify one universally optimal technology.

Figure 2 compares the media qualitatively across bandwidth, range, propagation delay, energy efficiency, environmental sensitivity, and Doppler sensitivity. The chart illustrates that strengths on one axis can coincide with limitations on another; it is not a measured benchmark and does not establish an optimal score for every deployment.



Technology / Communication Medium	Propagation Delay	Communication Range	Bandwidth	Doppler Effect	Energy Efficiency	Environmental Sensitivity
LEO Satellites and Optical Fiber	High	Low	High	Low	Low	Low
FSO and UOWC	Medium	Medium	Medium	Medium	Medium	Medium
RF	Medium	Medium	Medium	Medium	High	High
Underwater Acoustic	Low	Medium	Low	Low	Medium	High
Terrestrial Cellular Networks	Very High	Low	Very High	High	High	Medium

Figure 2. Qualitative comparison of representative communication media and infrastructures—LEO satellite/optical-fiber links, FSO/UOWC, RF, underwater acoustic, and terrestrial cellular networks—across propagation delay, range, bandwidth, Doppler effect, energy efficiency, and environmental sensitivity. The scores show scenario-dependent tendencies rather than measured or universally normalized performance.

Examination of the Multi-Criteria Chart and the Balance of Capabilities Across the Transmission Media

The qualitative comparison in Figure 2 illustrates trade-offs rather than universal numerical rankings. FSO links can support high data rates and low energy per transmitted bit under favorable conditions, but atmospheric attenuation, turbulence, cloud blockage, and pointing error can interrupt the link [22]. Reported demonstration rates are configuration-specific and should not be generalized to every inter-satellite or cross-domain optical link.

Figure 2 represents underwater acoustic communication as delay-dominated and bandwidth-constrained relative to radio and optical media. Acoustics remains a principal option when a longer underwater wireless reach is required, while UOWC can provide higher rates over shorter, alignment-dependent paths [7], [8]. The chart is qualitative: it does not establish universal performance scores or imply that every application has the same real-time threshold. These trade-offs motivate adaptive media selection and gateway queue management.

The Physics of Radio-Wave Propagation and the Limitations of Spectrum and Penetration

Radio-frequency links form the backbone of terrestrial and satellite communications. Their performance nevertheless depends on frequency, path geometry, weather, and atmospheric state. At microwave and millimeter-wave frequencies, rain attenuation and molecular absorption can be important, while ionospheric effects can disturb some satellite links; link budgets and adaptive coding should therefore use band- and scenario-specific propagation models [22].

Seawater is electrically conductive, and electromagnetic attenuation increases strongly with frequency. Conventional microwave links therefore have very limited underwater reach, whereas lower-frequency approaches trade usable bandwidth against antenna size, power, and deployment complexity [6]. Acoustic and optical links are consequently the principal practical wireless options for most underwater sensor-network scenarios, with their respective delay, bandwidth, and alignment constraints [7], [8].

The Subsurface Acoustic Channel: Reach–Delay Trade-offs

Acoustic communication is the principal long-range wireless option underwater, but the channel is shaped by spreading, absorption, surface and seabed reflections, Doppler, and spatially varying sound speed [8]. Temperature, salinity, and pressure

alter the sound-speed profile and can refract propagation paths, so link design and routing should use environmental measurements or robust channel models rather than a fixed straight-line assumption.
Because acoustic propagation is slow relative to radio and optical propagation, delay spread and multipath can produce substantial intersymbol interference, with severity dependent on range, geometry, bandwidth, and environment [8]. Equalization, multicarrier modulation, coding, and adaptive rate selection are therefore evaluated jointly rather than assigned a universal delay or performance value.

Optical Links: High-Rate Potential and Alignment Constraints

Optical space links offer high data-rate potential but require accurate pointing, acquisition, and tracking. Demonstration results are mission- and geometry-specific and should not be generalized to terabit-per-second inter-satellite links over arbitrary distances. Atmospheric paths additionally face cloud, turbulence, and attenuation, whereas inter-satellite paths primarily face geometry and terminal-tracking constraints [22].
UOWC uses wavelengths in the blue–green region because attenuation is often lower there than at other optical wavelengths. Controlled experiments have demonstrated gigabit-per-second transmission over meter-scale links, but range and rate vary markedly with water type, turbidity, scattering, ambient light, transmitter power, receiver sensitivity, and alignment [7]. It should therefore be treated as a high-rate short-range complement to acoustics, not as a medium with a single universal range.

Table 3. Evidence-based comparison of heterogeneous communication media. The entries emphasize deployment-dependent roles, strengths, constraints, and representative sources.

Medium	Domains and role	Evidence-based strength	Principal constraint	Best-fit use / sources
RF / millimeter-wave	Above-water space, air, ground, and gateway links.	Mature wide-area connectivity with frequency- and geometry-specific link design.	Higher bands can suffer atmospheric loss; seawater severely attenuates conventional RF.	Above-water backhaul and gateway links; [21], [6], [22], [7], [5]
Free-space optical	Space and aerial line-of-sight links.	High-rate potential and narrow-beam reuse under favorable conditions.	Cloud, turbulence, and pointing make performance geometry- and weather-dependent.	Inter-satellite or aerial line-of-sight backhaul; [22]
Underwater acoustic	Subsurface sensing, control, and longer-reach wireless links.	Principal reach-oriented underwater option; sound propagates at approximately 1,500 m/s.	Limited bandwidth, long delay, multipath, Doppler, and channel variability.	Delay-tolerant subsea telemetry and control; [6], [8], [14]
Underwater optical	Short-range subsea offload and local high-rate links.	Blue-green links have demonstrated Gbit/s over meter-scale controlled paths.	Range and rate depend on water, turbidity, scattering, light, power, sensitivity, and alignment.	AUV docking, sensor data offload, and local clusters; [7], [5]

Table 3 shows that cross-domain design is a media-composition problem rather than a search for one universally superior link. RF and free-space optical links are strongest above water, whereas acoustic and underwater optical links address complementary reach-rate needs below water. Accordingly, the surface gateway must select, buffer, or translate across media as channel state and service priority change.
The central media trade-off is joint optimization of reach, rate, delay, energy, and correlated availability rather than isolated link optimization. A policy that favors an instantaneous optical rate may lose availability under alignment or weather disturbances, while an acoustic path can preserve underwater reach at the cost of delay and buffer occupancy [22], [7], [8]. This synthesis therefore identifies a need for shared cross-medium traces and test procedures that compare switching thresholds, correlated failures, and energy per successfully delivered unit of information across the air–water boundary [7], [5].

Environmental Sensitivity, Heterogeneous Interference, and Physical-Layer Security

Environmental conditions can impair several communication media at the same time, but the affected links and severity depend on frequency, geometry, weather, sea state, and deployment [22], [7], [8]. For example, precipitation or cloud can degrade selected radio or optical paths, while sea-state changes can alter an acoustic channel. Correlated outages are therefore a scenario to be modeled and measured, not a universal consequence of every storm; multi-link availability analysis should use environment-specific statistical data.
Physical-media characteristics influence attack exposure but do not guarantee security. Narrow-beam optical links can reduce interception opportunities, yet pointing, terminal compromise, side channels, and denial-of-service remain relevant; broadcast acoustic links face different interception, spoofing, and jamming risks [3]. Multimodal gateways may switch or reduce rate under interference when an alternative link is available, but the response must follow measured channel state and policy rather than an assumed immediate or universally successful transition.

- **PROTOCOL CONVERGENCE, ROUTING, AND THE ROLE OF INTELLIGENT SURFACE GATEWAYS**

Cross-domain networking requires a logical layer that accommodates different delay, loss, bandwidth, disruption, and contact patterns. Conventional Internet transports were designed primarily for comparatively stable end-to-end paths, whereas underwater acoustic and some space or mobile links can be long-delay or intermittently connected [8], [14]. This difference does not require an entirely separate protocol in every case; transport adaptation, DTN overlays, and multimodal surface gateways are candidate mechanisms for interoperability [14], [5].

Protocol-Stack Heterogeneity and the Architecture of Delay-Tolerant Networks

Conventional end-to-end transports can perform poorly when long or variable acoustic delay, intermittent contacts, and non-congestion losses are interpreted as terrestrial congestion [8]. DTN is therefore a candidate overlay for disrupted cross-domain paths. The Bundle Protocol Version 7 (BPv7) supports persistent store-and-forward delivery without assuming a continuously available end-to-end path [14]; it is not, however, a universal replacement for every upper-layer protocol.

BPv7 nodes can store bundles persistently and forward them when a suitable contact becomes available [14]. Earlier bundle-protocol designs associated custody transfer with hop-by-hop responsibility, whereas BPv7 does not retain custody transfer as a core protocol feature; such reliability functions are handled separately. DTN can improve delivery opportunity under disruption, but it does not guarantee delivery and still requires storage, routing, security, and contact-management policies.

Intelligent Surface Buoys as Multi-Range Multimodal Gateways

The air–water boundary is a major integration point because direct signal propagation across it is difficult for many conventional underwater and above-water technologies [5]. Surface vessels and buoys are common multimodal gateways because they can host in-water acoustic or optical interfaces together with above-water radio or optical interfaces. Their hardware can combine low-power controllers with embedded processors, but energy and processing trade-offs depend on workload, platform size, and contact schedule rather than yielding a universal optimum.

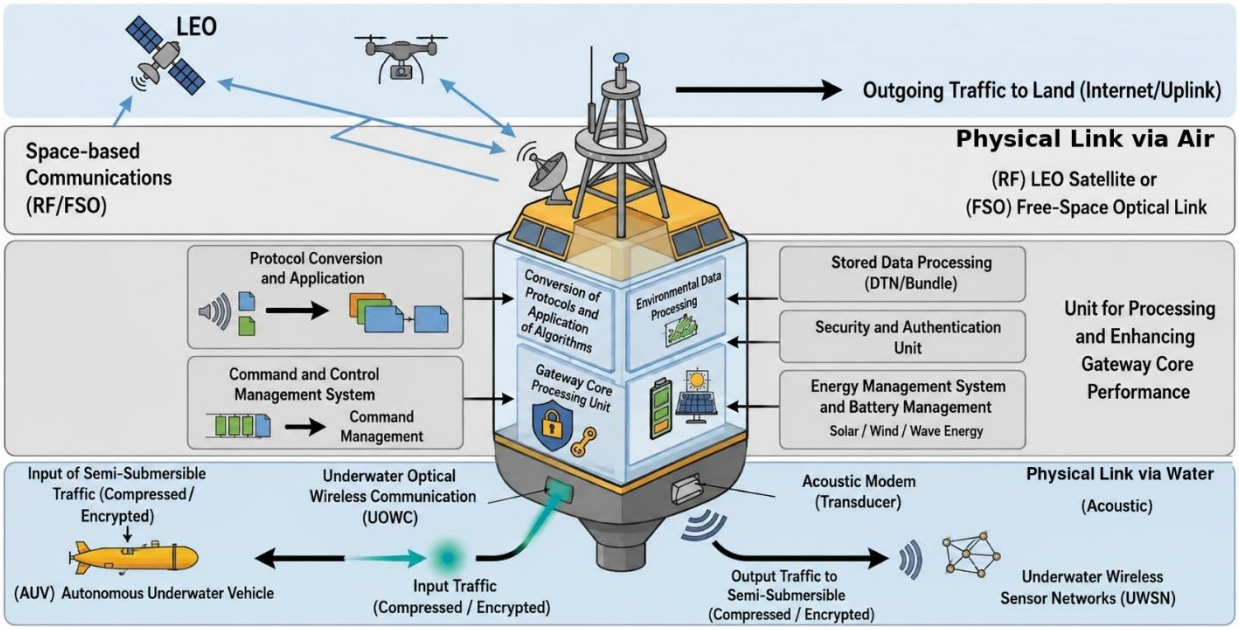


Figure 3. Functional architecture of an intelligent surface-gateway buoy that connects satellite/aerial, terrestrial, and underwater networks through RF/FSO, acoustic, and UOWC interfaces. The gateway integrates protocol conversion, buffering, security, processing, command and control, and energy management.

Adaptive Cross-Domain Routing Algorithms and Queue Management

Cross-domain routing must accommodate time-varying topology and heterogeneous link costs. In underwater networks, depth-based routing can forward packets without full geographic coordinates, while other geographic, opportunistic, or contact-aware strategies may be used at surface, aerial, and space layers [19], [6]. A gateway may translate routing context between domains, but no mandatory transformation from depth-based routing (DBR) to a single geographic protocol, such as greedy perimeter stateless routing (GPSR), has been established.

The large capacity mismatch between high-rate optical or radio uplinks and lower-rate, delay-dominated acoustic links can create gateway-buffer congestion [7], [8]. Priority scheduling, admission control, and active queue management are candidate mechanisms, but their parameters must reflect traffic criticality, measured service rate, storage, energy, and disruption duration. No single data-rate pair or queue policy applies to all deployments.

Protocol-Translation Mechanisms and Real-Time Data Bridging

Cross-domain gateways may encapsulate, aggregate, fragment, or translate frames when moving data between underwater sensor protocols and Internet Protocol (IP)-based upstream networks. Internet Protocol version 6 (IPv6) encapsulation is one possible implementation, while BPv7 provides another mechanism for carrying application data across disrupted heterogeneous paths [14], [5]. Processing overhead and addressing choices should be evaluated for the selected protocol stack rather than assumed to be negligible.

Middleware at a cross-domain gateway can monitor contacts and open data-offloading windows when an upstream link is available [14], [5]. Compression, aggregation, or duplicate suppression may reduce transmitted volume, but their value depends on content, computation, energy, and delay. Security processing should preserve end-to-end policy and authenticated key management; protocol translation does not inherently require replacing transport-layer cryptography or treating every acoustic link as insecure [3], [14].

Time-Synchronization Challenges and Error-Recovery Mechanisms

Time synchronization is challenging because localization and scheduled access require a shared reference, while underwater acoustic delay varies with range and sound-speed profile. Global Navigation Satellite System (GNSS) signals used by surface or aerial nodes are strongly attenuated in seawater, so submerged nodes typically require acoustic or local synchronization methods [19], [8]. Required accuracy is application-specific and should not be assigned a universal microsecond target.

Underwater synchronization methods can estimate propagation delay and clock drift using exchanged acoustic timing messages, with a surface gateway acting as a reference when connectivity permits [19]. Error-control design likewise depends on channel state and latency: forward-error correction, erasure coding, interleaving, and selective retransmission are complementary options rather than guarantees of complete recovery [8].

Table 4. Comparison of routing and protocol mechanisms for heterogeneous cross-domain paths. Benefits and limitations are stated for their intended operating conditions rather than as universal performance guarantees.

Mechanism	Operating basis	Cross-domain value	Main limitation	Use / sources
BPv7 / DTN	Persistent store-and-forward across scheduled or opportunistic contacts.	Maintains forwarding progress when a continuous end-to-end path is unavailable.	Requires storage, contact management, and expiry policy; delivery is not guaranteed, and custody transfer is not a core BPv7 feature.	Disrupted multi-domain paths; [14]
Depth / geographic / opportunistic routing	Uses depth, position, neighbor availability, or forwarding opportunity in the underwater segment.	Can avoid maintaining a complete global topology and adapt forwarding to local link conditions.	Performance depends on node density, void handling, mobility, localization quality, energy, and channel variability.	Underwater sensor networks; [19], [6]
Contact-aware routing	Uses predicted or observed contact windows among mobile relays and gateways.	Aligns forwarding with intermittent LEO, UAV, vessel, or buoy connectivity.	Prediction error, missed contacts, storage limits, and waiting delay can reduce benefit.	Scheduled cross-domain relays; [1], [14], [5]
Learning-assisted routing	Maps observed network state to routing actions through trained models or reinforcement learning.	Can incorporate multiple time-varying link and resource indicators in one decision policy.	Training data, generalization, observability, computation, stability, and safety require validation.	Selected dynamic space–air–ground scenarios; [23], [24]
Gateway translation and queue control	Encapsulates, fragments, aggregates, translates, and schedules traffic at the air-water boundary.	Bridges incompatible link stacks and absorbs rate or contact mismatches.	Buffer pressure, reassembly state, security semantics, and end-to-end transparency complicate operation.	Surface buoys and vessels; [7], [3], [14], [5]

Table 4 separates continuity mechanisms from optimization mechanisms. BPv7/DTN and contact-aware forwarding tolerate disruption, underwater routing selects feasible local paths, and learning can assist decisions only when its observations and training remain valid. The gateway therefore remains a protocol and queue-management boundary rather than a transparent relay.

At the gateway level, protocol convergence is a state-management problem rather than simple header translation. Encapsulation and aggregation can reduce upstream overhead, but fragmentation, buffering, expiry, and security processing may obscure end-to-end service semantics when contacts are missed [3], [14], [5]. A specific open question is how a gateway should preserve application priority, authentication context, and recoverable forwarding state across acoustic, optical, and IP segments without exhausting constrained storage or compute.
At the routing level, DTN and contact-aware forwarding trade immediate delivery for persistence under disruption, whereas geographic, opportunistic, or learning-assisted methods trade control knowledge and computation for more adaptive path selection [19], [23], [6], [24], [14]. Failures arise from routing voids, contact-prediction error, stale state, expired bundles, or unavailable credentials. Comparative validation should therefore apply common contact traces and jointly report delivery, information age, buffer occupancy, energy, expiry, and security overhead instead of optimizing one metric in isolation [3], [14], [5].

INTELLIGENT NETWORK MANAGEMENT, SOFTWARE-DEFINED ARCHITECTURE, AND RESOURCE ALLOCATION

Cross-domain network management couples routing, resource allocation, mobility, energy, and intermittent connectivity. Traditional distributed control can incur high update overhead or slow convergence when topology changes rapidly, motivating programmable SDN/NFV architectures and hierarchical control [1], [18], [29]. These mechanisms provide a design framework for AI-assisted decisions, but do not by themselves eliminate packet loss or control-plane delay.

The Software-Defined Control-Layer Architecture in Heterogeneous Domains

SDN separates control logic from packet-forwarding functions through logically centralized control. In SAGSIN, controller placement and control-plane reachability remain challenging because propagation delay and intermittent links vary across layers. A distributed or hierarchical design can place local control functions nearer selected domains while coordinating summarized state with higher-level controllers [29]; the appropriate placement depends on topology, failure model, and control latency. Southbound control interfaces designed for stable terrestrial links may require adaptation for delayed or intermittently connected segments. OpenFlow-like mechanisms can still provide programmable forwarding, but timer, state-synchronization, and failover behavior must be engineered for the relevant cross-domain delay and disruption model [29].

Network Function Virtualization and Network Slicing for Strategic Applications

Network function virtualization enables functions such as firewalls, intrusion detection, load balancing, and protocol acceleration to run as software on shared compute infrastructure. Together with SDN, it supports network slicing and flexible service deployment, subject to compute, orchestration, and isolation limits [16].

Network slicing allows multiple logical services with different performance and security objectives to share physical infrastructure [16]. A safety-critical control service and a delay-tolerant environmental-monitoring service, for example, may receive different resource policies. Isolation mechanisms aim to limit cross-slice interference, but strict performance and security isolation are not automatically guaranteed during overload or attack and remain an engineering and verification challenge.

Closed-Loop Management, Machine Learning, and Intelligent Automation

As network scale and channel variability increase, manual configuration and fixed heuristics may become insufficient for some control tasks. AI-assisted analysis can be integrated with SDN in a closed-loop management concept, but autonomy, stability, and safety must be validated for the deployment [15], [17], [18]. Figure 4 presents four conceptual functions—monitoring, analysis, decision, and action—without implying that deep neural networks must execute every function continuously.

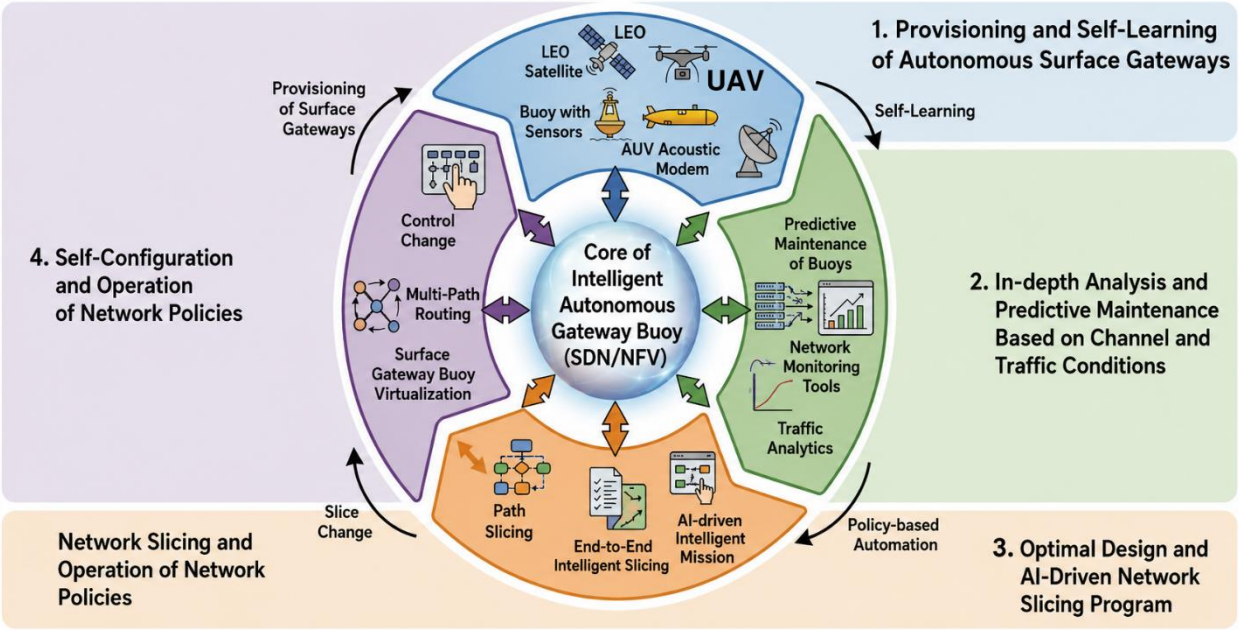


Figure 4. Four-stage AI-assisted management loop for an intelligent surface-gateway buoy: provisioning, telemetry analysis and predictive maintenance, network slicing, and policy reconfiguration. SDN and NFV support closed-loop coordination among monitoring, decision, and control functions.

Figure 4 depicts a closed-loop management concept in which telemetry—such as channel quality, node energy, buffer state, and contact geometry—is supplied to an analyzer. Deep reinforcement learning (DRL) can formulate selected resource-allocation or routing problems as Markov decision processes, with state, action, and reward definitions tailored to the deployment [15], [25], [23], [17]. Resulting policies remain dependent on training coverage, observability, safety constraints, and computational resources.

Centralized learning can require substantial telemetry transfer, motivating federated learning (FL) at selected edge nodes. In FL, nodes train locally and exchange model updates instead of raw datasets [26]. This can reduce some raw-data movement, but communication overhead, data that are not independent and identically distributed (non-IID), node availability, poisoning, update leakage, and privacy protection remain open constraints; FL does not by itself guarantee confidentiality or autonomous healing.

Intelligent Cyber Resilience and Intrusion Detection at Strategic Chokepoints

Artificial intelligence can support anomaly detection and adaptive defense, but integrated cross-domain networks remain exposed to spoofing, malicious-data injection, jamming, and denial-of-service attacks across heterogeneous links [3]. For maritime

chokepoints such as the Strait of Hormuz, the operational importance of traffic and energy transit increases the consequence of control-plane disruption, without implying that any single network failure necessarily produces a specified outcome [13].
Zero-trust principles require continuous authentication, authorization, and least-privilege access rather than trust based only on network location [27]. Edge intrusion-detection and behavioral analysis can flag anomalous traffic, while an SDN controller can apply a policy response; detection accuracy and response time depend on models, telemetry, adversarial behavior, and link availability [3]. Frequency hopping is another possible anti-jamming measure, but its effectiveness depends on synchronization, key management, bandwidth, and threat assumptions.

Table 5. Comparative roles of programmable management, AI, and cyber-resilience mechanisms. Each mechanism is paired with its intended benefit, principal limitation, and representative evidence.

Mechanism	Control or data locus	Intended benefit	Principal limitation	Use / sources
Hierarchical SDN	Global and domain controllers with programmable forwarding nodes.	Coordinates policy and resource decisions across heterogeneous layers.	Controller placement, delayed control links, state synchronization, timer behavior, and failover must match topology.	Cross-domain control; [18], [29]
NFV and slicing	Software functions on shared edge, gateway, or cloud compute.	Supports flexible service chains and differentiated resource or security policies.	Isolation under overload or attack, orchestration overhead, and limited compute remain open verification issues.	Service-specific virtual networks; [16], [18]
DRL closed-loop control	Telemetry-driven policy at a controller or capable edge node.	Adapts selected routing, scheduling, or resource decisions to observed state.	Reward design, training stability, generalization, safety, observability, and inference cost constrain deployment.	Dynamic resource management; [15], [25], [17]
Federated learning	Local training at distributed nodes with shared model updates.	Reduces some movement of raw data and supports collaborative model improvement.	Non-IID data distributions, update traffic, poisoning, leakage, node availability, and aggregation robustness remain concerns.	Distributed intelligent transmission; [26]
Zero trust and edge intrusion detection	Continuous identity and policy checks plus distributed telemetry analysis.	Limits implicit trust and supports anomaly detection and policy response near affected domains.	Effectiveness depends on credentials, telemetry quality, threat assumptions, false alarms, and secure coordination.	Cross-domain access and defense; [27], [3]

Table 5 indicates that programmability, learning, and security are mutually dependent rather than interchangeable. SDN and NFV provide control and deployment structure; DRL and federated learning provide conditional adaptation; and zero-trust or intrusion-detection mechanisms constrain who and what may influence the loop. A practical architecture must therefore co-design control reachability, compute placement, model assurance, and security policy.
For programmable management, the main trade-off is global coordination versus local autonomy. Hierarchical SDN and NFV can place policy and functions across domains, but delayed control paths, controller partitions, orchestration overhead, limited gateway compute, and imperfect slice isolation can invalidate a nominally centralized decision [16], [18], [29]. A key validation question is which control and virtualized functions must remain local during disconnection, and how their state should be reconciled when higher-level connectivity returns.
The synthesis also reveals a control-assurance loop: learning depends on telemetry, telemetry integrity depends on authentication and detection, and enforcement depends on reachable controllers and sufficient edge compute. Consequently, AI-enabled control should be evaluated with uncertainty, fallback behavior, control overhead, inference cost, false alarms, and recovery after controller or link partition—not only average reward [25], [27], [17], [26], [3], [29]. Open priorities include safe degradation to non-learning policies, robustness to poisoned or non-IID updates, and verification of isolation when control and security functions share constrained gateways.

- **FUTURE TRENDS, RESEARCH FRONTIERS, AND OPEN CHALLENGES**

Space–Air–Ground–Ocean Integrated Networks still face theoretical and practical challenges in cross-domain propagation, protocol interoperability, management, security, energy, experimentation, and standardization [3], [4]. This section discusses selected research directions relevant to future sixth-generation and beyond-6G systems without assigning a fixed deployment timeline.

Cross-Domain Quantum Communications and Security Limitations

Quantum key distribution (QKD) has been demonstrated over satellite-to-ground links [28], while laboratory underwater QKD experiments have also established feasibility over controlled optical water channels [30]. These results do not yet demonstrate an operational end-to-end space–air–water QKD service. Atmospheric loss, water absorption and scattering, background light, pointing, trusted-node design, and quantum-memory limitations remain major cross-domain research challenges.
The integration gap is therefore key management across heterogeneous trust and contact domains, not the existence of individual point-to-point demonstrations. Research should compare trusted-node and relay assumptions, acquisition and reacquisition under mobility, key freshness during disruption, and the processing and storage burden imposed on surface gateways before claiming end-to-end operational security [28], [3], [30].

Battery-Free Sensor Networks and Sustainable Energy in the Ocean Depths

Limited battery lifetime is a central constraint for long-lived underwater sensors. Recent battery-free prototypes have harvested acoustic energy and used piezo-acoustic backscatter to transmit underwater image data, demonstrating a feasible design direction under controlled conditions [12]. This acoustic approach is distinct from conventional radio-frequency simultaneous wireless information and power transfer (SWIPT) surveyed for terrestrial wireless networks [11]. Transfer efficiency, range, transducer size, source availability, and multi-access protocols remain open deployment constraints.

For integrated networks, the relevant question is whether harvested energy can sustain a defined sensing, computation, and communication duty cycle under realistic contacts—not whether a single prototype can operate without a conventional battery. Future studies should jointly report harvested energy, sensing quality, delivered information, latency, and outage behavior, and should validate durability, multi-access operation, and gateway scheduling beyond controlled demonstrations [11], [5], [12].

Semantic Data Integration and Quality of Experience in the Three-Dimensional Environment

Semantic communication is an emerging direction in which a system transmits task-relevant representations rather than reproducing every source bit. In four-domain networks, this approach may reduce traffic when edge inference can identify information relevant to a sensing or control task [31], [4]. Evaluation should therefore include task accuracy, semantic distortion, robustness, latency, and model cost in addition to conventional quality-of-service metrics; common definitions and benchmarks remain open research needs.

The remaining integration challenge is whether semantic models generalize across domains, tasks, channel states, and adversarial inputs while fitting the compute and update budget of edge gateways. Comparative studies should use common tasks and report task accuracy, semantic distortion, latency, energy, model size, update traffic, and failure behavior alongside conventional bit-level metrics [31], [26], [4]. This would distinguish genuine end-to-end benefit from traffic reduction obtained only under a favorable model or dataset.

CONCLUSION

The transition from isolated communication systems toward Space–Air–Ground–Ocean Integrated Networks is motivated by wide-area connectivity, environmental monitoring, and resilient service across remote regions. This review has examined the different constraints of space, aerial, surface, and underwater layers. Their heterogeneous propagation, capacity, delay, and disruption characteristics limit direct use of unmodified terrestrial protocol assumptions. DTN and persistent store-and-forward operation are principal candidate mechanisms for intermittently connected paths, alongside transport adaptation, gateway processing, and contact-aware routing [8], [14], [5].

Intelligent buoys and vessels can serve as translation gateways and edge processors, while SDN, NFV, and learning-based methods can assist queue management, routing, and resource allocation. These mechanisms remain conditional on trustworthy telemetry, controller reachability, computation, energy, and isolation. Progress toward deployable four-domain systems therefore requires validated cross-domain security, sustainable underwater energy, interoperable protocols, realistic experiments, and standards; ubiquitous and instantaneous connectivity should be treated as a long-term objective rather than an established capability [3], [4].

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