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A Survey on Nature-Inspired Control Methods for IoT and Communication Networks

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Abstract

Modern Internet of Things (IoT) and communication networks operate under dynamic, large-scale, and resource-constrained conditions where conventional control can falter. This survey synthesizes 108 peer-reviewed (including preprints) studies (2007–2025) on nature-inspired control mapped to the TCP/IP stack across the classes of network functions. The survey introduces a three-axis taxonomy (TCP/IP layer × biological metaphor × function) and a unified KPI scheme with a normalization formula to compare heterogeneous reports. Aggregated evidence indicates typical gains of 20–50% energy reduction, 25–40% delivery-ratio improvement, 10–35% latency reduction, and > 0.95 F1 for immune-inspired intrusion detection, when compared to canonical baselines. This survey further makes explicit how few studies validate on real hardware or under adversarial conditions. Moreover, this survey analyzes real-time constraints, hyperparameter sensitivity, and integration pathways with 6LoWPAN/RPL, TSCH/6TiSCH, MQTT, and CoAP, outlining steps toward deployable, explainable, and deterministic nature-inspired control.

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1. Introduction

Networks are one of the essential components of many systems in the world. The Internet is a well-known example of a network where many devices are connected to each other. Modern communication networks—including the Internet of Things (IoT), Wireless Sensor Networks (WSNs), and cloud-connected embedded systems—face increasing demands in scalability, energy efficiency, and autonomous control. In particular, IoT networks often operate in resource-constrained, dynamic, and decentralized environments where conventional control mechanisms may struggle.

These networks (for example) are composed of a large number of nodes (e.g., devices, services, and people), links (e.g., wired or wireless connections, personal relations), and layers (e.g., Autonomous Systems: AS [1]). Thus, current network systems are becoming increasingly large-scale and complex.

In the past, various studies have proposed control methods for networks, such as access control, routing, and Quality of Service (QoS) control. However, these methods often assume smaller and less complex networks than those existing today. As a result, previous control methods can become impractical when applied to modern large-scale and highly complex network systems.

On the other hand, a successful large-scale complex network system already exists in *nature*. The natural world is composed of numerous nodes (e.g., quarks, nuclei, molecules, humans, solar systems, galaxies) and links (e.g., van Der Waals forces, device connections, human relationships). Moreover, hierarchical structures are found universally in nature, forming complex multi-scale organizations from micro to macro scales. For example, substances are formed by the aggregation of atoms and molecules. Atoms themselves are composed of even smaller components such as nuclei, protons, electrons, and quarks. Both organic materials (such as organisms) and inorganic materials (such as minerals) share such hierarchical organization. The Earth is composed of living entities and minerals, and forms part of the solar system, which itself is part of a galaxy, and galaxies form the cosmos. This hierarchical nature–from subatomic particles to the cosmos–is often represented by the symbolic Snake of Ouroboros, where micro and macro scales are interlinked. Importantly, control mechanisms in nature often emerge from local behaviors of components at lower hierarchical levels.

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Motivation

Inspired by the natural world's control mechanisms, this survey reviews novel solutions to the challenges faced by current large-scale complex network systems. Many researchers have attempted to design effective operations for network systems by mimicking strategies observed in nature. Nature-inspired approaches can be applied not only to basic communication operations such as access control but also to higher-level applications such as security and QoS control. Therefore, this survey systematically reviews nature-inspired network control strategies, with a focus on mapping them onto the TCP/IP protocol suite. This survey primarily covers literature published over the period 2007–2025.

Survey methodology

This survey was conducted using a systematic approach to ensure comprehensive coverage and fairness. The primary sources include peer-reviewed journals, top-tier conferences, and preprints from databases such as IEEE Xplore, ACM Digital Library, SpringerLink, and arXiv. The selection criteria are as follows:

- The work must explicitly focus on network control techniques inspired by natural phenomena.
- Only papers published between 2007 and 2025 were considered.
- Studies must address control mechanisms that can be mapped to one or more layers of the TCP/IP protocol suite.
- Both theoretical proposals and practical implementations were included.

After the initial collection, papers were classified based on the TCP/IP protocol layer (Physical (PHY), Medium Access Control (MAC), Network, Transport, Application, or Cross-Layer) and the type of natural phenomenon mimicked (e.g., biological evolution, swarm intelligence, molecular dynamics). Furthermore, papers were also analyzed to extract the core technological achievements and limitations. This survey includes both wired and wireless communication networks, but places particular emphasis on IoT-related systems, which increasingly adopt nature-inspired methods to address their unique control challenges.

Contribution

The contributions of this survey are summarized as follows:

- The relationship between nature-inspired network control and the TCP/IP protocol suite is systematically summarized.
- The technological evolution of nature-inspired strategies over time is organized and analyzed.
- Open challenges and future research directions are discussed based on the findings.

Organization

The rest of this survey is organized as follows. Section 2 explains the preliminaries of this study. Section 3 summarizes the survey scope and classification of This survey. Section 4 reviews nature-inspired network control strategies, mapping them to the TCP/IP protocol layers. Section 5 shows a comparative evaluation of the surveyed studies. Section 6 discusses limitations identified in the literature and suggests future research directions. Section 7 concludes this survey and discusses future perspectives.

2. Preliminaries

This section provides the preliminaries necessary to understand the content of this survey. Specifically, this section describes the Open Systems Interconnection (OSI) reference model and the TCP/IP protocol suite, both of which are fundamental concepts in network communications.

2.1. OSI Reference Model

The OSI reference model [2] (OSI model) was developed by the International Organization for Standardization (ISO) to standardize the communication functions of network systems by organizing them into a layered architecture.

Prior to the development of the OSI model, computer networks were often constructed using products from a single vendor, making interoperability between different vendors' equipment difficult. As networks became widespread, there was an increasing demand for vendor-independent communication, leading to the formulation of open design policies. Today, although the OSI model is rarely implemented exactly as specified, it remains a fundamental conceptual model for understanding network communications.

The OSI model consists of seven layers, each responsible for specific aspects of network communication, as follows:

Layer 1: Physical Layer

This layer defines the hardware-related physical properties required for communication. It specifies aspects such as the cable types, connector shapes, clocking, and voltage levels of the electrical signals used. Its primary role is to establish a physical transmission path between devices.

Layer 2: Data Link Layer

This layer enables data communication between directly connected nodes. It introduces a meaningful unit of transmission called a *frame*, and provides mechanisms for data validity checking, error correction, and node addressing. Protocols at this layer often closely interact with physical layer characteristics and determine connection types (topologies).

Layer 3: Network Layer

This layer enables communication between nodes across different networks. By tracing adjacent networks sequentially, it allows data packets to reach any destination node, even when the source and destination are far apart.

Layer 4: Transport Layer

This layer ensures reliable end-to-end data transfer through error control and flow control mechanisms. It divides data into smaller segments, manages sequencing, error correction, and retransmissions if necessary.

Layer 5: Session Layer

This layer establishes, manages, and terminates communication sessions between applications. It provides mechanisms to maintain the continuity of sessions and distinguish between different communication streams.

Layer 6: Presentation Layer

This layer defines data representation formats, including text, images, streaming data, encryption, compression methods, and character encoding standards. It ensures that data exchanged between different systems can be correctly interpreted.

Layer 7: Application Layer

This layer provides network services directly to end-user applications. It defines protocols and interfaces that enable users and software processes to access network resources and services. Typical functions include communication between client and server applications, file transfer, remote login, email, directory services, name resolution, and distributed information sharing.

2.2. TCP/IP Protocol Suite

The TCP/IP protocol suite is a set of communication protocols that has become the de facto standard for computer networks, including the Internet. Its layered structure is defined by the Internet Engineering Task Force (IETF) in RFC 1122 [3].

Unlike the OSI model, the TCP/IP protocol suite was not designed to align with the OSI layers, and no formal mapping to OSI exists. The IETF explicitly states that TCP/IP development was pursued independently of the OSI framework.

The TCP/IP protocol suite is composed of four layers, each responsible for the following functions:

Layer 1: Network Access Layer

This layer handles the delivery of TCP/IP packets over the physical network. It is designed to be independent of specific hardware technologies, supporting a wide range of access methods, frame formats, and media types.

Layer 2: Internet Layer

This layer enables internet-working across multiple heterogeneous networks, providing logical addressing and routing mechanisms to deliver packets to their intended destinations.

	OSI reference model	TCP/IP protocol suite	
Layer7	Application	Application	Layer4
Layer6	Presentation		
Layer5	Session		
Layer4	Transport	Transport	Layer3
Layer3	Network	Internet	Layer2
Layer2	Data link	Network access	Layer1
Layer1	Physical		

Figure 1. Comparison between the OSI reference model and the TCP/IP protocol suite (example mapping).

Layer 3: Transport Layer

This layer provides communication services between applications running on different hosts. It ensures reliable data transfer, detects and recovers from errors when necessary, and supports bi-directional communication.

Layer 4: Application Layer

This layer offers services and protocols for end-user applications to communicate over the network, enabling data exchange between software processes.

Several studies and textbooks have attempted to map the TCP/IP protocol suite onto the OSI model (as shown in Figure 1). However, it is important to note that such mappings are approximations and inconsistent with the original intentions of RFC 1122 and other primary IETF documents. The IETF emphasizes that the TCP/IP protocols were developed independently without adhering to the OSI model.

3. Survey scope and classification

To ensure a comprehensive and systematic coverage of the field, this survey adopts a multi-stage methodology inspired by best practices in scientific reviews. The process consists of three phases: literature collection, relevance screening, and structured classification.

3.1. Literature collection

This survey conducted an extensive literature search across leading scholarly repositories, including IEEE Xplore, ACM Digital Library, SpringerLink, and arXiv. The target period was set to 2007–2025, covering both foundational work and the latest developments in nature-inspired network control. Rather than relying strictly on keyword matching, this survey adopted a flexible two-stage approach. First, a broad pool of candidate papers was retrieved using search terms such

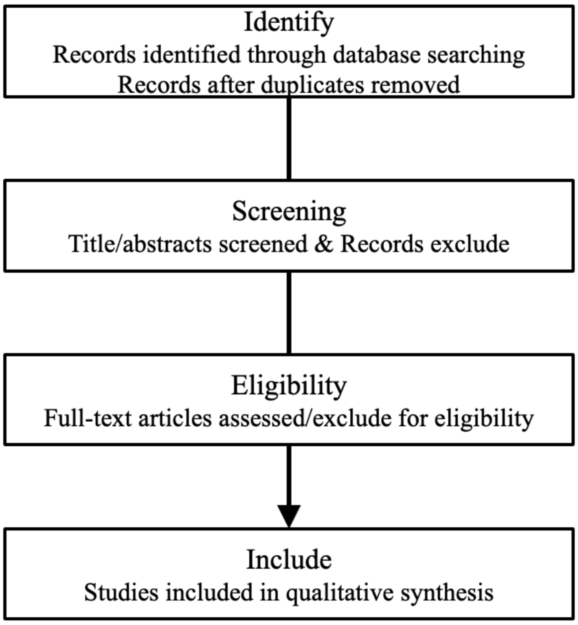

Figure 2. PRISMA 2020 flow diagram for study selection.

Table 1. PRISMA 2020 counts for study selection (corresponding to Figure 2).

Records identified (database searching)	**128**
Duplicates removed	**12**
Records screened (titles/abstracts)	**116**
Records excluded	**4**
Full-text articles assessed for eligibility	**112**
Full-text articles excluded (with reasons)	**4**
Studies included in qualitative synthesis	**108**

as *nature-inspired*, *bio-inspired*, *biologically motivated*, and *biomimetic*. Second, each paper was manually examined for topical relevance, ensuring inclusion of impactful works that may not explicitly use standardized keywords but clearly meet the survey's scope.

This hybrid method enabled the inclusion of studies spanning diverse application domains, modeling paradigms, and evaluation techniques–some of which may employ unique terminology but are nevertheless grounded in nature-inspired mechanisms for network control. This survey then manually examined each candidate paper to confirm its relevance to network control and its explicit or implicit grounding in natural phenomena. This flexible approach enabled the inclusion of impactful studies that might not use standard keywords but nonetheless align with the scope and objectives of this survey. This survey follows PRISMA 2020 reporting; the flow and the data count are provided in Figure 2 and Table 1, respectively.

3.2. Inclusion criteria

A study was considered eligible for inclusion if it satisfied all of the following criteria:

- It proposes or evaluates a network control mechanism, such as routing, MAC scheduling, congestion control, service discovery, clustering, and security;
- The technique is inspired by natural phenomena (e.g., swarm intelligence, evolutionary dynamics, neural processing, immune systems, physical/chemical principles);
- The mechanism can be mapped to one or more layers of the TCP/IP protocol suite, following RFC1122;
- The study contains technical substance (algorithmic design, simulation, testbed evaluation, or analytical results).

Purely conceptual or position papers without implementation/evaluation were excluded.

3.3. Final corpus and classification framework

After applying the selection criteria, this survey obtained a corpus of 108 primary studies spanning WSNs, IoT, cognitive radio, VANETs, edge/fog/cloud, and SDN. To facilitate structured analysis, each paper was classified along three dimensions: TCP/IP layer (Network Access, Internet, Transport, Application, Cross-Layer), natural phenomenon (Swarm, Evolutionary, Neural, Immune, Ecological, Physical/Chemical), and targeted function (Routing, MAC/Power, Congestion/Rate, Clustering/Topology, Service Discovery/Composition, Security/Anomaly Detection, Resource Allocation/Offloading, Coverage). This forms the analytical basis for the layer-wise survey (Section 4) and comparative evaluation (Section 5).

3.4. Classification Dimensions

This survey classifies each study by (i) locus of control in the **TCP/IP stack** (RFC 1122), (ii) **biological or physical metaphor**, and (iii) **targeted network function**. A Cross-Layer category captures studies manipulating parameters across multiple layers. Metaphor categories include swarm intelligence (ants/bees/birds/fish), evolutionary computation (Genetic Algorithm (GA), Differential Evolution (DE), and Particle Swarm Optimization (PSO)), neural models (spike coding, distributed inference), immune mechanisms (clonal/negative selection, danger theory), ecological dynamics (predator–prey, population growth), and physical/chemical processes (diffusion, thermodynamic analogies). The function axis covers routing/path selection; MAC and power control; congestion/rate control; clustering/topology; service discovery/composition; security/anomaly detection; resource allocation/offloading; and coverage optimization. This three-axis structure supports mapping between analogies and protocol-layer functionality and reveals trends such

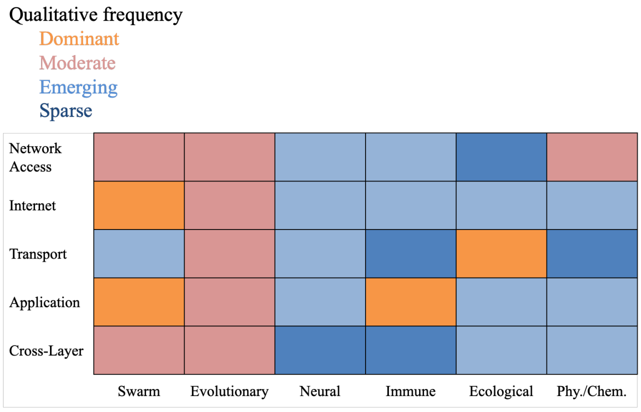

Figure 3. Taxonomy matrix across TCP/IP layer × biological metaphor × targeted function. Cell entries show qualitative intensity (Dominant/Moderate/Emerging/Sparse).

as the predominance of swarm-inspired techniques in routing/clustering, and the emergence of ecological/neural models in congestion control and distributed inference. The author coded layer/metaphor/function per study, systematically reviewing and resolving any coding ambiguities according to pre-specified decision rules. Note that *Nature-inspired* (*Bio-inspired*) denotes algorithms that instantiate a natural mechanism (signals, interactions, or adaptation law) in the control loop; bio-plausible denotes analogy-level borrowing without preserving interaction laws. A compact visual taxonomy (layer × metaphor × function, qualitative frequencies) is provided in Figure 3.

To support a structured and scalable analysis of the 108 selected studies, this survey classifies each work along three independent dimensions: (i) the corresponding **TCP/IP protocol layer**, (ii) the **type of natural phenomenon** mimicked, and (iii) the **targeted network function**. These classification axes are designed to reflect both technical relevance and conceptual inspiration, and serve as the foundation for the subsequent layer-wise analysis in Section 4 and the comparative discussion in Section 5.

TCP/IP Protocol Layer. This survey adopts the four-layer structure of the TCP/IP protocol suite as specified in RFC 1122: *Network Access*, *Internet*, *Transport*, and *Application* layers. In addition, a fifth category, *Cross-Layer*, is introduced to capture studies that simultaneously manipulate parameters across multiple layers. Each included work is mapped to one or more of these layers based on the locus of its control strategy. For instance, a nature-inspired MAC scheduler belongs to the network access layer, while an immune-based anomaly detector for cloud environments is categorized under the application layer.

This layered view supports vertical decomposition and enables consistent alignment with architectural roles in modern network stacks.

Natural Phenomenon Mimicked. The second dimension concerns the biological or physical source of inspiration. This survey identifies six dominant categories based on the modeling metaphors and algorithmic strategies described in the literature:

- **Swarm Intelligence:** Collective behaviors such as those of ants, bees, birds, and fish; commonly applied to routing, clustering, and coverage optimization.
- **Evolutionary Computation:** Population-based search paradigms including GAs, DE, and hybrid crossover-based heuristics.
- **Neural Models:** Spike coding, asynchronous signal propagation, and distributed inference modeled after the cerebral cortex.
- **Immune Systems:** Mechanisms such as clonal selection, negative selection, and danger theory, used for intrusion detection and trust modeling.
- **Ecological Dynamics:** Predator–prey interactions, logistic population growth, and foraging strategies adapted for rate and load control.
- **Physical and Chemical Processes:** Diffusion equations, advection models, and thermodynamic analogies employed in PHY/MAC design and performance modeling.

By identifying these sources of inspiration, this survey enables functional interpretation of bio-analogies, and facilitates the analysis of how certain metaphors—e.g., pheromone trails or immune responses—are repeatedly used across different protocol layers and network objectives.

Targeted Network Function. The third axis considers the specific control function addressed. The surveyed studies span a wide range of network challenges, which this survey groups as follows:

- **Routing and Path Selection**
- **Medium Access and Power Control**
- **Congestion and Rate Control**
- **Clustering and Topology Formation**
- **Service Discovery and Composition**
- **Security and Anomaly Detection**
- **Resource Allocation and Offloading**
- **Coverage Optimization**

Each study is associated with one or more of these categories, depending on the primary outcome metrics reported (e.g., delivery ratio, energy consumption, latency, coverage). This function-based view enables cross-layer comparisons and reveals convergence in biological strategies applied to similar technical goals.

Rationale and Alignment. The three-dimensional classification introduced here allows this survey to organize the diverse literature into a coherent analytical structure. It enables mapping between natural analogies and protocol-layer functionality, and reveals trends such as the predominance of swarm-inspired techniques in routing and clustering, or the emergence of ecological and neural models in congestion control and distributed inference. This structure directly supports the taxonomy and layer-wise review in Section 4.

3.5. Summary of Classification Results

This survey applied the three-dimensional classification framework—TCP/IP protocol layer, type of natural phenomenon mimicked, and targeted network function—to a corpus of 108 studies. The results provide a comprehensive overview of the current state of nature-inspired network control and reveal key trends across layers and problem domains.

Distribution by TCP/IP Layer. The reviewed works were first mapped to the functional layers of the TCP/IP protocol suite, as defined in RFC 1122. The resulting distribution is as follows:

- **Network Access Layer:** 27 studies
- **Internet Layer:** 13 studies
- **Transport Layer:** 12 studies
- **Application Layer:** 45 studies
- **Cross-Layer:** 11 studies

Application layer studies dominate the corpus, highlighting increasing research attention toward security, service orchestration, and intelligent offloading. While cross-layer strategies are less numerous, they show promise for holistic system optimization and multi-objective trade-offs.

Distribution by Natural Phenomenon. [1]

The types of natural inspiration adopted in the surveyed studies span six major categories, with the following relative frequencies (note: one study may map to multiple categories):

- **Swarm Intelligence:** 34 studies (∼30%)
- **Evolutionary Computation:** 20 studies (∼18%)
- **Neural Models:** 11 studies (∼10%)
- **Immune Systems:** 13 studies (∼12%)
- **Ecological Dynamics:** 16 studies (∼14%)
- **Physical/Chemical Processes:** 9 studies (∼8%)

[1]The total number of papers does not match the total number of surveyed papers (108) because some studies were inspired by more than one natural phenomenon.

Distribution by Network Function. [2]

The targeted network functionalities cover a wide range of topics. The approximate proportions (non-exclusive) are:

- **Routing and Path Selection:** 27 studies (∼24%)
- **Medium Access and Power Control:** 15 studies (∼15%)
- **Congestion and Rate Control:** 14 studies (∼13%)
- **Clustering and Topology Formation:** 14 studies (∼13%)
- **Security and Anomaly Detection:** 15 studies (∼15%)
- **Service Discovery and Composition:** 8 studies (∼7%)
- **Resource Allocation and Offloading:** 8 studies (∼7%)
- **Coverage Optimization:** 9 studies (∼8%)

Counts align with the qualitative matrix in Figure 3.

4. Layer-wise survey of nature-inspired strategies

This survey reviews the state-of-the-art control strategies in network systems inspired by natural phenomena. In particular, this survey focuses on how various nature-inspired approaches have been applied across different layers of the TCP/IP protocol suite. This section organizes nature-inspired network control strategies according to their correspondence with the TCP/IP protocol suite. Although the TCP/IP model does not directly correspond to the OSI model, this survey adopts the TCP/IP layer classification, consisting of the network access, internet, transport, and application layers, following RFC 1122. This classification aims to provide a comprehensive and structured understanding of how nature-inspired ideas contribute to network control across layers and scales.

Nature-inspired approaches have been proposed for each of these layers, targeting different network functions such as physical connectivity, media access control, routing, congestion control, and application level communication optimization.

The following subsections review the literature for each TCP/IP layer, categorizing the strategies according to the primary function addressed by the nature-inspired mechanism.

4.1. Strategies on network access layer

The network access layer embraces nature-inspired work from the radiating element up to distributed MAC. This survey groups the 26 papers into five technological themes

[2]This does not correspond to the total number of surveyed papers (108) because some papers deal with more than one function.

and highlights their biological metaphors, core achievements, and open issues that a critical reviewer is likely to raise.

Nature-inspired physical layers and antennas

Nature-shaped geometries are exploited to shrink size, widen bandwidth, or enable new carriers. Skeleton/skin analogues guide a microwave backscatter system for passive IoT that survives mechanical stress and self-heals [4]. Molecular diffusion models realise a "chemical" PHY for 6G in RF-denied spaces [5], while a protein-based bio-cyber interface connects nano-sensors [6]. Radial-symmetry petals and fractal leaves miniaturise sub-GHz dielectric and micro-strip antennas without compromising gain [7, 8]. Although simulations and 3-D-printed prototypes are reported, few papers characterise mutual coupling or reliability under realistic MIMO/EMC constraints; future measurement campaigns on larger arrays and harsh environments would strengthen the claims. The method proposed in [9] is also a good example of obtaining broadband characteristics with a minimum of design variables by transferring the complex contours acquired by the leaf for efficient light collection directly to the electromagnetic patch.

Self-organising MAC

Coupled-oscillator synchronisation (fireflies, frog choruses) aligns transmission slots in wireless Local Area Networks (WLANs) via SP-MAC [10], whereas Z-MAC blends CSMA and TDMA patterns influenced by zebra stripe adaptation to balance contention and duty-cycle [11]. A related strategy to SP-MAC is proposed in [12]. Layered-MAC mirrors animal sleep/wake rhythms to insert "energy-protected" guard periods in WSNs [13], and a target-tracking MAC lets sensor "sentinels" imitate flock sentry behaviour [14]. Reviewers often question scalability and fairness under heterogeneous traffic loads. Only SP-MAC provides convergence proofs; the rest rely on ns-2/ns-3 studies with $\leq$ 200 nodes. Large-scale test-beds and formal stability analyses remain open. A related study is the Kuramoto-model-based resource allocation (fair slot allocation) in wireless networks [15]. Reference [16] proposes an energy-saving self-organizing control for WSNs inspired by the croaking behavior of frogs. This proposal allows for autonomous energy control for WSNs. Brain spike communication has been proposed for thousands of microchip sensors [17]. By simulating spike event transmission in the cerebral cortex, information can be expressed only in terms of event times, and reliable communication can be achieved without synchronous signals. Moreover, by mimicking the asynchronous distributed processing of the brain, each node can operate with autonomous timing without a central clock, thus reducing power consumption and interference even in large networks.

Energy-aware duty-cycling and power control

A bat sonar heuristic schedules node wake-ups, extending lifetime by 45% without increasing end-to-end delay [18]. Grey-wolf optimisation trims LoRa TX-power in crop fields (average -3.1 dBm per hop) [19], and probabilistic rain-pollen coverage (target-problem geometry) jointly sizes radio ranges (transmission power) [20]. Yet collision-induced retries are not budgeted in the lifetime models. Future work should integrate traffic bursts and capture channel-busy time experimentally. Recent fuzzy-cuckoo-search variants prolong WSN lifetime by more than 30% through contextual CH re-selection [21] and adaptive two-tier CS-LEACH scheduling [22]. PSO was introduced [23] to achieve simultaneous power supply and high data efficiency in an IoT system equipped with visible light communication for indoor agriculture and warehouse robots. Moreover, Power allocation with hybrid Grey Wolf and Crow Search in MIMO-NOMA systems is proposed in [24]. This study aims to optimize power allocation for wireless communications.

MAC-layer security and anomaly detection

Artificial-immune mechanisms detect man-in-the-middle frames at the link layer within 5 ms [25], while GA-tuned antibody populations flag botnet flows with 96% F1 score [26]. A reviewer will ask about adversarial robustness and incremental retraining cost; none of the studies evaluate poisoning attacks or concept drift.

Multi-objective optimisation of access networks

Golden-angle phyllotaxis and PSO balance delay and energy in large-scale IoT meshes [27]. Ant–pheromone workload migration smooths smart-healthcare hotspots [28]. While the meta-heuristics converge faster than canonical PSO/GA baselines, parameter sensitivity—particularly to colony size and evaporation rate—remains under-explored, making reproducibility difficult. Reference [29] is a study that considers traffic as a fluid and analyzes cellular downlink interference using a continuous fluid approximation (dimensionless flow field). The results lead to the construction of a lightweight input model for network planning tools. A bio-inspired QoS-oriented handover model improves continuity in heterogeneous wireless networks, balancing delay and packet loss during vertical handovers under multi-radio conditions [30].

Summary of network access layer strategies

Network access research exhibits a clear split between hardware-centric biomimetic structures and software-centric self-organisation. The former pushes novel materials and shapes but lacks system-level evaluation; the latter shows promising scalability but still depends on idealised simulators. Bridging these gaps—e.g., verifying oscillator-based MAC atop bio-layer antennas in outdoor test-beds—constitutes a fertile ground for future cross-disciplinary studies.

4.2. Strategies on internet layer

The Internet layer deals with logical addressing and multi-hop routing. This survey reviews 13 studies classified as Internet-layer research and groups them under four technological themes, emphasising their biological metaphors, principal achievements, and reviewer-relevant limitations.

Swarm-intelligence routing protocols

Collective foraging and flight behaviours dominate: early BeeIP demonstrates bee-dance–style path selection in Mobile Ad Hoc Networks (MANETs) [31]; more recent ant-colony optimisation (ACO) schemes colour pheromone by service class to support heterogeneous IoT traffic [32]. Energy-centred hybrids mix ACO with PSO or butterfly search, extending network lifetime by 35% – 40% in disaster and industrial deployments [33]. Grey-wolf, Harris-hawk and glow-worm variants improve convergence speed or exploration diversity in dense WSNs [34–36]. Although simulation gains are compelling, scalability tests with (> 500) nodes and real mobility traces remain scarce–a point that experienced reviewers are likely to raise.

Bio-morphic path formation and remodelling

Several protocols copy growth processes of network-forming organisms. A MANET algorithm reproduces fungal mycelium expansion to obtain low-stretch Steiner graphs with self-healing shortcuts [37]. Physarum-style nutrient flow, fused with immune self/non-self discrimination, yields a trusted routing protocol for mobile WSNs that restores connectivity within 2 s of node capture [38]. These morphology-aware schemes elegantly merge discovery and optimisation, yet their periodic global diffusion steps question scalability beyond (10^3) nodes.

QoS-aware and domain-specific routing

Smart-grid, LoRa Neighborhood Area Network (NAN) and Industry 4.0 scenarios motivate customised meta-heuristics that couple energy balancing with traffic classes. Faheem *et al.* embed immune-inspired trust metrics into an ACO framework for WSN-based smart grids, cutting packet loss by 21% while meeting latency budgets [39]. A butterfly–PSO cluster approach for disaster IoT reduces delay jitter by 29% [40], whereas an African-buffalo guided LoRa mesh shortens hop count by 18% under deep-indoor fading [41]. Service-differentiated ACO for Named-Data Networking allocates colour-coded pheromone to guarantee per-class delay bounds [42]. Most studies, however, do not report analytical latency guarantees or coexistence tests with baseline IP routing.

Brain- and spike-inspired networking

Two recent works draw on neural spike coding to handle disruption-tolerant links. A distributed Spiking Neural Network (SNN) jointly minimises delay and packet loss in DTN routing, surpassing spray-and-wait by up to 42% in delivery ratio [43]. SNN control overhead and on-node training cost, however, are yet to be quantified; future research should benchmark energy and memory footprints against lighter heuristics.

Summary of internet layer strategies

Internet-layer work is still routing-centric: adaptive meta-heuristics inspired by ants, bees, wolves, hawks, or glow-worms account for most contributions, while a smaller but visionary strand uses self-remodelling organisms (fungi, Physarum) to merge discovery and healing. Domain-specific variants embed QoS, trust, or energy metrics for smart-grid, LoRa, and NDN scenarios, and two exploratory studies import neural-spike coding for disruption-tolerant paths. Although simulator results show delivery-ratio or lifetime gains of 25–40%, reproducible evidence on hardware beyond a few hundred nodes, systematic meta-parameter tuning, and resilience to routing attacks remain scarce. Demonstrating nature-inspired routing under real mobility, interference, and adversarial conditions therefore emerges as the critical next step toward deployable Internet-layer control.

4.3. Strategies on transport layer

Recent work maps population dynamics and adaptive foraging in ecology to congestion/rate-control problems, seeking simultaneous gains in throughput, fairness, and stability. This survey clusters 12 Transport layer studies into three themes.

Population-dynamics congestion control

TCP Symbiosis models single-flow growth with the logistic equation and multi-flow interaction with Lotka–Volterra competition, stabilising high-BDP links while improving fairness [44]. In addition, Yao et al.'s self-adaptive rate control, which formulates predator-prey competition in terms of the Lotka-Volterra equation, reports a 12% jitter reduction for WLAN streams with different priorities [45]. Nature-inspired self-adaptive rate-control for multi-priority streaming traffic extends the same idea to heterogeneous queues [45], while an antelope-herd analogy shapes rate adjustment for real-time video in WSNs [46]. The mathematical ecological model in [46] was applied to the WSN video stream and showed that a high frame rate of 91% could be maintained. BICC discretises predator–prey equations, using queue length (predator) and window size (prey) as coupled variables to speed convergence and equalise throughput [47].

Multi-species interaction models

The three-trophic regulator B-IOCC adds a resource species to Lotka–Volterra and cuts queue occupancy by 22% under mixed IoT loads [48]. A particle-swarm–guided extension to the standard PSO explores parameter space online and lifts delivery ratio by 15% in dense WSNs [49].

Adaptive foraging and meta-heuristics

A Tasmanian-devil foraging cycle plus fuzzy inference tunes CoAP window sizes, boosting packet-delivery ratio on lossy links [50]. Adaptive Rendezvous-Based Congestion Control diffuses ant pheromone to disperse hotspots and extend first-node-death time by 27% [51]. Hybrid Crow-Search–Grey-Wolf optimisation further balances energy and delay under bursty traffic [52], and intelligent congestion control based on glow-worm luminescence achieves 96% accuracy in hotspot prediction [53]. Load-balancing for industrial IoT merges bacterial chemotaxis with learning automata to raise link utilisation by 11% [54]. Finally, brain-inspired spike coding selects transmission schedules resilient to bursty interference, outperforming Sprinkler and PSR by up to 42% in delivery ratio [55].

Summary of transport layer strategies

Transport layer research splits into two streams. Population-model controllers (logistic, predator–prey, tri-trophic) deliver mathematically provable stability and fairness, yet lack large-scale in-situ evidence. Meta-heuristic foraging schemes (devil, ant, crow, wolf, brain spikes) show strong adaptability in IoT and WSN test-beds but depend on many hyper-parameters and rarely prove stability. Bridging these gaps–e.g., validating population-dynamics controllers on real IoT hardware, or deriving sensitivity analyses for meta-heuristics–emerges as the key step toward deployable nature-inspired transport control.

4.4. Strategies on application layer

Nature-inspired design has now reached the top layer of the TCP/IP stack. A systematic review of 46 primary studies shows that their aims fall into four technical thrusts. Together these pillars capture the full breadth of nature-inspired work at the application layer and provide an organising lens for the discussion that follows. The remainder of this subsection elaborates each pillar in turn, highlighting representative algorithms, and quantified benefits.

Service discovery and composition

Nature-inspired heuristics support application-layer orchestration not only via service lookup but also via control-plane and aggregator selection in IoT/SDN systems. For WSN-based IoT, the Osprey-optimised SWARAM scheme selects energy-efficient cluster heads, stabilising application-level data aggregation [56]. In software-defined infrastructures, hybrid HSA–PSO and SA–MCSDN formulations optimise multi-controller placement, reducing control-plane latency and improving resilience [57, 58], while in SDN-based LEO satellite networks a joint optimisation of controller placement and switch assignment balances delay and load [59]. For energy-harvesting WSNs, a Whale–Grey-Wolf hybrid improves clustering efficiency under dynamic energy budgets [60]. A nature-inspired adaptive WSN architecture further explores how application-layer functions can reconfigure in response to network context [61]. For true service discovery, a QoS-aware IoT discovery method that combines Whale Optimisation and GAs improves multi-attribute matching [62], and the GREPHRO optimisation duo illustrates how nature-inspired search assists IoT-scale orchestration decisions [63].

Security and anomaly detection

Nature-inspired security can be framed by organism-level principles–immunity, adaptation, and co-evolution–providing design patterns that complement classical cryptographic controls [64]. For industrial IoT, an artificial immunity based distributed and fast anomaly detection achieves low-latency decisions across edge nodes while preserving accuracy under workload bursts [65]. Immune-system analogues span host, fog, and cloud levels. A kind of nature-inspired IDS is proposed in [66]. ImmuneGAN integrates generative modelling with artificial-immune mechanisms for IoT threat detection [67], and DAIS presents a deep artificial immune system for intrusion detection in IoT ecosystems [68]. At the edge of the application stack, a nature-inspired multilevel security protocol secures data aggregation and routing in IoT WSNs [69]. Additional nature-inspired defences include adaptive network stabilisation with Artificial Bee Colony optimisation for cyber-security [70], a nature-inspired hybrid deep-learning NID model [71], an improved privacy-preserving IoT scheme [72], and edge-oriented intrusion classification that couples nature-inspired optimisation with ensemble learning [73]. For cloud/industrial settings, hybrid nature-inspired feature selection with Random Forest yields scalable Cloud-IDS pipelines [74], while an Artificial Bee Colony–based homogenisation mapping targets secure spectrum/resource allocation in industrial WLANs [75]. Explainability for Software-Defined IoT is addressed by an explainable nature-inspired attack detection framework [76]. In agriculture IoT deployments, a bio-inspired Q-learning model with customized shards jointly optimizes QoS and security, adapting control policies to field dynamics while maintaining confidentiality and throughput [77]. Moreover, the framework of simulation of nature-inspired security mechanisms is studied in [78]

Edge–fog–cloud resource management

Reference [79] proposes to use the Whale Optimization Algorithm to arrange smart grid control tasks in such a way that both shortest response and least energy are achieved, simultaneously reducing bandwidth bottlenecks and carbon emissions from cloud processing. Elephant–sine–cosine hybrids sustain surge workloads with lower energy and latency in cloud load-balancing [80]. It can stably distribute high data rate cloud load with energy savings and low latency. In [81], energy efficiency optimization in Mobile Edge Computing (MEC) environments using PSO is proposed to maximize safety computation efficiency and spectral efficiency even under RF power supply, which is expected to contribute to large-scale IoT energy reduction such as smart factories. In [82], furthermore, task scheduling based on the

Grey Wolf algorithm in vehicular fog computing is proposed. A comprehensive optimization method for UAV-assisted fog computing is realized with Enhanced Ant Colony System, PSO, and Fuzzy-PID [83]. A bee-foraging analogue further addresses content-distribution in mega-constellation satellite networks: Liu et al. dynamically relocate popular objects among Low Earth Orbit nodes, raising cache-hit ratio by 17% and cutting back-haul traffic by 13% [84]. As part of resource management, network performance evaluation is required. A method has been proposed to model the transmission rate used by wireless terminals using advection-diffusion phenomena, which leads to theoretical throughput estimation and may evolve into a mechanism to achieve network quality estimation [85]. There is also a study that evaluates network performance by applying Fluid Model Analysis to Software Defined WANs [86]. This study proposes a continuum approximation of the network by considering individual packets/flows as "fluid" and treating nodes as continuous mass sources, which allows for a hydrodynamic analysis of the traffic spread. This research is also expected to develop into a mechanism to realize network quality estimation.

Network stability and coverage

Research on stabilizing network structure has been actively studied. Recent theory also clarifies how structure and control co-evolve in nature-inspired networks. Especially, [87] formalize the principles that link local interaction rules to global controllability and stability. If the network structure can be stabilized, it will be possible to run various applications on it. Among them, [88, 89] propose autonomous decentralized methods for constructing network structures (clusters) based on the diffusion equation and/or Huygens' principle. In addition, [90] studies Honey-Bee Mating Optimization (HBMO), an optimal strategy for clusterheads based on bee mating behavior. Furthermore, [91] proposed an AVOCA (African Vulture Optimization-based Clustering Algorithm) based on the foraging behavior of African vultures. K-BCO, which combines K-means and Bee Colony Optimization, has been proposed [92] for WSNs with mixed heterogeneous nodes. This research result achieves both high data rate transmission and long-lived cluster structure with a minimum number of nodes, and prevents network overload. Clustering can also be used to save energy in networks. As a clustering using GA, there is a mechanism to simultaneously optimize the total amount of energy for communication and computation in a two-layer clustering [93]. Reorganization of the constructed clusters has also been studied. In [94], an ensemble heuristic combining the Artificial Fish Swarm Algorithm (AFSA) and the Bees Algorithm dynamically reorganizes clusters by selecting cluster heads based on residual energy and node proximity. In sensor networks, it is also important to increase the coverage of an area by sensors in order to maintain the network. Therefore, [95] proposes a two-stage metaheuristic GARWOA that combines a GA and Whale Optimization to achieve fast and accurate coverage optimization. Reference [96] also proposed and evaluated maximizing the coverage of a sensor network using coordinated flight (PSO) of a bird/fish flock. This study aimed to reduce deployment cost and computational complexity while achieving maximum coverage in sensor heterogeneous and obstacle environments. In [97], moreover, the marine predator algorithm was applied to the sensor network coverage problem with the aim of achieving both full coverage of the observation area and reduced node movement energy while minimizing sensor density. An area coverage method for WSNs is proposed that combines fuzzy logic and the Shuffled Frog-Leaping algorithm to achieve full coverage with the fewest number of active nodes and maximize net lifetime [98]. In addition, GWO has been used to realise load-balanced clustering for sustainable WSNs [99]. Furthermore, [100] proposes a method of clustering BeeCup for power saving of mobile learning.

Summary of application layer strategies

Application layer nature-inspired research now bifurcates into two dominant streams. Security/discovery frameworks (immune, ant, whale, bee, spider-monkey) deliver striking gains but seldom test adversarial robustness or large-scale churn. Resource-management heuristics (pheromone, wolf, elephant, bat, krill, starling) cut latency and energy in edge/fog clouds, yet depend on many hyper-parameters and rarely prove stability. Rigorous adversarial evaluations, automated parameter tuning, and unified frameworks that merge discovery, security, and off-loading therefore represent the critical next frontiers for deployable nature-inspired application layer control.

4.5. Cross-cutting Considerations

Whereas the previous sections focused on single layers, a smaller body of work applies nature-inspired mechanisms across multiple layers to achieve end-to-end optimisation. The literature survey identifies 11 primary studies that explicitly manipulate parameters spanning at least two TCP/IP layers. This section categories them into two strands:

- Holistic routing and clustering optimisation
- Cognitive-radio adaptation

Cross-layer routing optimization

A study has been proposed to efficiently perform cross-layer routing in Underwater Acoustic Sensor Networks (UASNs) by coordinating the family unit migration of elephant herds with the synchronous luminescence and bacterial chemotaxis of fireflies and the flocking behavior of bird flocks [101]. Hybrid PSO-ILEACH (HPSO-ILEACH), a method that simultaneously optimizes clusterheads and routing paths with PSO and binary genetic operations, has been proposed to optimize data aggregation efficiency and energy consumption [102]. Reference [103] propose an enhanced ACO scheme for clustering-aware routing in vehicular ad hoc networks; by selecting the fittest relay nodes and adaptively tuning pheromone evaporation, their protocol reduces packet drops by more than seven-fold and prolongs the lifetimes of both cluster-heads and ordinary members. In [104], when WSNs are used as IoT infrastructure, cross-layer routing is realized to ensure high QoS (delay, throughput, packet loss, etc.) while reducing energy consumption. They report a significant reduction in packet loss rate and latency, and improved throughput, by using moonlight navigation (Moth Search), which mimics the movement of moths as they spiral and converge on their prey as a result of flying at a fixed angle and relying on the moonlight. Reference [105] also proposes a hybrid optimization algorithm that integrates multiple nature-inspired methods for both clustering and routing to increase the longevity of WSNs. Specifically, they propose a method that combines Grey Wolf Optimizer and ACO with PSO and show that it significantly reduces average energy consumption and also improves throughput and traffic dispersion. Reference [106] proposes to combine physical, MAC, and network layer information with Harris Hawk Optimization to simultaneously optimize cluster head selection and route construction. Simulations confirm a 19% increase in throughput and a 27% decrease in packet loss, as well as a 12% reduction in control overhead due to cross-layer. In [107], a method that combines clustering using the “Mayfly Optimization Algorithm” and routing using “Enhanced ACO” is proposed. The objective is to simultaneously solve high power consumption and packet loss due to multiple paths in an underwater WSN,

Cross-layer cognitive-radio adaptation

A chicken-swarm optimiser coupled with deep-belief-network sensing lifts detection probability from 0.58 to 0.81 under -10 dB SNR, while trimming energy by 11% [108]. Cross-layer cognitive-radio adaptation requires simultaneous optimization of spectrum perception and interference estimation at the physical layer, channel and transmit power control at the MAC layer, and cluster structure and route selection at the network layer. Recent biomimetic metaheuristics for WSNs (such as [109–111]) anticipate this multi-layer coordination framework.

Summary of cross layer strategies

Cross-layer nature-inspired work remains nascent–only 11 papers versus dozens in single-layer domains—but demonstrates clear potential. Joint MAC–routing schemes deliver holistic energy–QoS trade-offs, yet lack large-scale validation. Meta-heuristic stack optimisers achieve impressive delay and lifetime gains in SDN and WSN test-beds but depend on many hyper-parameters and rarely analyse stability. Cognitive-radio designs show robustness to spectrum dynamics, though security against malicious sensing remains unexplored. System-level experiments on dense, mobile, and adversarial networks–and automated tuning of cross-layer parameters–constitute the key research frontiers for deployable nature-inspired holistic optimisation.

5. Comparative evaluation

This survey now turns to a comparative evaluation of the surveyed studies, focusing on how effectively various nature-inspired strategies align with network control challenges, the degree of performance improvement they achieve, and their maturity for deployment in practical settings.

5.1. Nature-Inspired vs. Network Problem Matching

The surveyed literature exhibits a diverse but coherent mapping between natural metaphors and network control problems. This survey finds that specific classes of biological mechanisms tend to align naturally with certain categories of networking tasks:

- **Swarm Intelligence** is most frequently applied to problems involving distributed coordination and path discovery, such as routing, clustering, and service composition. ACO, bee foraging, and bird flocking analogies show strong compatibility with multi-agent search and redundancy-aware path planning.
- **Evolutionary Algorithms**, including GA, PSO, and hybrid crossovers, are commonly employed in resource allocation and configuration problems that involve parameter optimization under constraints. These are particularly suited to MAC scheduling, power control, and task offloading.
- **Immune System Models** are predominantly applied to security and anomaly detection, leveraging the metaphors of self/non-self discrimination and adaptive defense. These models have been especially impactful in IDS and trust-based routing protocols.
- **Neural and Spike-Inspired Models** are emerging in application domains requiring asynchronous or event-driven communication, such as disruption-tolerant networking and cognitive radio spectrum sensing.
- **Ecological Dynamics** (e.g., predator–prey systems, foraging behavior) map well to congestion and rate control problems, due to their ability to regulate competitive interactions over shared resources.
- **Physical and Chemical Processes** provide lightweight diffusion-based models for topology formation, MAC design, and coverage optimization in sensor networks.

This survey concludes that the metaphorical alignment between biological systems and network functionalities is not arbitrary but structurally meaningful. However, this alignment also introduces design biases; for instance, swarm-based systems are rarely employed for parameter estimation or memory-intensive tasks.

Table 2. Selected nature-inspired control schemes across TCP/IP layers.

Layer	Nature Paradigm	Function	Ref.
Network Access	Firefly sync	MAC scheduling	[10]
Network Access	Grey Wolf	TX power control	[19]
Internet	Ant colony	QoS routing	[32]
Internet	Fungal growth	Self-healing	[37]
Transport	Predator–prey	Congestion control	[44]
Application	Immune	IDS	[67]
Application	Whale opt.	Offloading	[79]
Cross-Layer	PSO	Routing + clustering	[102]

5.2. Quantitative Performance Gains

This section synthesizes heterogeneous reports using a simple normalization to obtain relative gains g with respect to their baselines:

$$g = \begin{cases} \dfrac{\text{baseline} - \text{proposed}}{\text{baseline}} & \text{(lower-is-better: energy, latency, jitte} \\ \dfrac{\text{proposed} - \text{baseline}}{\text{baseline}} & \text{(higher-is-better: delivery, coverage,} \end{cases} \quad (1)$$

Across the 108 reviewed studies, nature-inspired strategies consistently report improvements along four key axes:

- **Energy Efficiency**: Swarm- and evolutionary-based protocols achieve 20-50% reductions in energy consumption, especially in WSNs/IoT. Duty-cycling informed by bat/frog heuristics often extends lifetime without added latency.
- **Delivery Ratio and Coverage**: Metaheuristics (e.g., Glow-worm Swarm, Marine Predator) show 30-40% gains in delivery/coverage versus canonical baselines (LEACH/AODV).
- **Latency and Jitter**: Coordinated migration (ant–butterfly hybrids) and neural spike strategies reduce latency by 10–35%, with IDSs reporting sub-10ms inference in some fog/cloud tests.
- **Security and Robustness**: Immune-based detection frequently exceeds 0.95 F1, with good tolerance to class imbalance on resource-constrained platforms.

Table 2 lists eight representative schemes across layers (e.g., Firefly-sync MAC, ACO QoS-routing, predator-prey congestion control, immune IDS), grounding these axes in concrete cases. While these reports are promising, this survey notes that some rely on idealized simulators with limited node counts or simplified channels; only a subset provide testbed or adversarial/mobility validation (see Section 6.1). Given this heterogeneity, the ranges are indicative rather than meta-analytic effect sizes (see Figure 4).

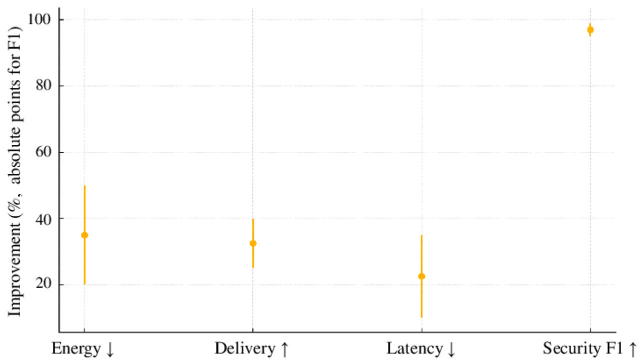

Figure 4. Aggregated performance ranges based on Eq. (1): energy↓, delivery↑, latency↓, and security (F1)↑, aggregated from the surveyed literature.

5.3. Deployment Readiness and Scalability

The deployment maturity of nature-inspired network control techniques varies significantly across categories:

- **High readiness**: Certain swarm-based routing and MAC protocols have been prototyped on real WSN testbeds and integrated into simulation platforms like NS-3. These methods often require minimal computation and have tunable convergence behavior.
- **Moderate readiness**: Evolutionary and ecological algorithms demonstrate strong adaptability but often depend on multiple hyper-parameters, making online deployment sensitive to environmental drift and system dynamics.
- **Low readiness**: Neural and immune models exhibit promising accuracy and biological plausibility but face challenges related to model complexity, training cost, and reproducibility across platforms.
- **Cross-layer designs**: While holistic cross-layer control using bio-metaheuristics is conceptually powerful, few studies report system-level validation or integration with existing protocol stacks.

This survey highlights that real-world deployment demands not only performance gains but also considerations of computational overhead, convergence stability, parameter sensitivity, and security robustness. Future studies should move beyond simulation benchmarks to validate nature-inspired strategies on dense, mobile, and adversarial network environments.

6. Challenges and future directions

Although nature-inspired approaches to network control have demonstrated promising capabilities across multiple protocol layers, several challenges remain before these techniques can be reliably deployed in real-world, large-scale, and adversarial environments. This section outlines key limitations identified in the literature and suggests future research directions.

6.1. Validation Beyond Simulation

Many studies rely on evaluations in idealized simulators–often with limited node counts, simplified topologies, or static traffic. Only a minority validate on physical testbeds (e.g., WSN motes, mobile ad hoc, edge-cloud), and security-oriented studies rarely test adversarial manipulation (poisoning, spoofing, replay). Future work should prioritize reproducible experiments on diverse hardware platforms and realistic mobility/interference. Datasets and testbed configurations should be shared to enable comparative benchmarking. This survey tags each primary study by evaluation modality (simulation, emulation, testbed, adversarial). This makes explicit how few works validate on real hardware or under adversarial stress. Threat-model reporting (poisoning, spoofing, replay/jamming) alongside runtime overhead is encouraged.

6.2. Hyperparameter Sensitivity and Explainability

Most nature-inspired algorithms depend on multiple tunables (swarm size, pheromone decay, mutation rate, spike thresholds), yet few studies present systematic sensitivity analysis; many adopt single configurations without robustness checks. Explainability is also limited in spike-coding or hybrid immune models, hindering debugging and regulated deployment. Reporting sensitivity curves or confidence regions and adopting automated tuning (e.g., Bayesian optimization) are recommended. For interpretability, expose pheromone maps, fitness attribution by feature, and spike-threshold events as first-class logs.

6.3. Scalability and System Integration

Large-scale deployments (10^3+ nodes), high-density contention, and tight latency/bandwidth budgets are rarely explored; cross-layer schemes often sit outside standard protocol boundaries, complicating integration. Progress requires protocol co-design, modular architectures, and scalable performance modeling. For mission-critical IoT, practitioners require worst-case delay and jitter bounds. Nature-inspired controllers can respect time-slotted schedules (e.g., TSCH) and expose deadline-aware fitness functions. Admission control should be integrated to honor per-flow deadlines. A full real-time treatment is outside the scope, but this survey outlines these deployment hooks.

6.4. Unified Frameworks and Hybridization

Most strategies target single functions (routing or clustering) in isolation; few unify performance, security, and energy under a common control logic. Hybrid models (e.g., spike coding with immune filtering) remain rare but promising. A composable control loop can couple Routing (swarm), Security (immune/trust), and Offloading (evolutionary) under shared north-/south-bound APIs with clear failure-mode fallbacks. Such coupling allows consistent objectives (e.g., latency/energy/robustness) while retaining local adaptation at each layer.

6.5. Standardization and Adoption Readiness

Adoption is hindered by the lack of standard APIs, reusable modules, and lifecycle management (runtime adaptation, upgrades, retirement). An example of practical integration mapping is:

- **RPL/6LoWPAN**: pheromone-like link metrics as Objective Function (OF) extensions; colony size/evaporation as DAG repair tunables.
- **TSCH/6TiSCH**: oscillator synchronization (firefly/Kuramoto) for slot alignment; swarm-based channel-offset selection.
- **MQTT**: adaptive publish scheduling via ecological congestion models; priority-aware topic queues.
- **CoAP**: adaptive block size/RTO via predator–prey rate control; immune-inspired anomaly filters on Observe streams.

Deployment should also include transparency, audit logs, and operator override for human-in-the-loop assurance.

7. Conclusion

This survey has presented a comprehensive survey of nature-inspired control strategies in network systems, with a particular emphasis on their mapping to the TCP/IP protocol suite. By systematically classifying and analyzing 108 studies published between 2007 and 2025, This survey has highlighted the growing diversity, technical depth, and cross-disciplinary innovation present in this field.

Nature-inspired approaches have proven effective in addressing a wide range of networking challenges—from routing, MAC scheduling, and congestion control to security, clustering, and service discovery. These strategies draw on diverse biological metaphors, including swarm intelligence, evolutionary dynamics, neural signaling, immune defense, and ecological interactions. Through the classification framework introduced in Section 4, This survey has revealed how specific natural paradigms align structurally with distinct layers and functions of the TCP/IP protocol stack.

The comparative evaluation in Section 5 demonstrated consistent quantitative gains in energy efficiency, delivery ratio, and robustness across many studies. At the same time, This survey has critically assessed the limitations of current work, such as reliance on simulation, lack of parameter sensitivity analysis, and limited real-world deployments. Section 6 outlined several open challenges and suggested future directions, including the need for explainable and scalable models, unified frameworks that support multi-function optimization, and standardized interfaces for adoption in production systems.

This survey concludes that while nature-inspired techniques are still maturing, they offer a promising foundation for the next generation of adaptive, resilient, and self-organizing network control systems. Continued progress in this field will require not only algorithmic innovation, but also interdisciplinary collaboration, rigorous benchmarking, and the development of reusable platforms that bridge the gap between theory and deployment.

As IoT systems continue to grow in scale and complexity, the adoption of nature-inspired control paradigms may become a cornerstone for achieving autonomous, resilient, and energy-aware network operations.

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