A Survey of Bio-Inspired Protocols: Swarm Coordination and Adaptive Routing

Natural Solutions to Nature's Challenges

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Abstract

Nature is full of networks, from bees, to ants, to even fungi. Bio-inspired Protocols are a category of protocols that seek to use nature's networks to invent and improve our own. This paper will survey adaptive routing (also known as dynamic routing) and swarm coordination within bio-inspired protocols, with a focus on 4 different settings, and how each setting has unique challenges which protocols employ swarm coordination and adaptive routing to overcome.

Keywords: swarm, swarm coordination, swarm intelligence, adaptive routing, bio-inspired algorithms, bio-inspired protocols, FANET, VANET, IoT, WSN, underwater wireless sensor networks, UWSN, stigmergy, energy, efficiency, scalability, security, PSO, ACO, GSO, CH, Krill Herd, clustering, BICR, RDACO, BeeAdHoc, HOCOR, APAR, BICSF, ELAACR

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1. Introduction

Technological innovation is growing exponentially, but technological expansion is just beginning. Soon, drones will fill our skies, sensors and unmanned submarines will fill our oceans, and intelligent self-driving cars will fill our roads. These technologies share a common need: Communication. Specifically, decentralized communication, networks of individual agents coordinating and self-organizing within a group to achieve a common goal. However, enabling drones to communicate in the sky has vastly different challenges than sensor networks communicating underwater. The intuition behind bio-inspired protocols is simple: model technological communication networks based on the existing natural communication networks that have adapted to thrive in their environments. Existing survey papers study bio-inspired protocols and algorithms within a single domain. This paper will unify research across airborne, terrestrial, and underwater environments to illustrate the unique challenges our modern technologies face, and how bio-inspired protocols overcome these challenges. We will lay the groundwork for our study by defining foundational concepts, then we will survey the challenges of the four domains, so that we can study several bio-inspired algorithms and protocols, regarding their swarm and adaptive routing attributes across these domains.

2. Fundamentals

While distinctly different, many technical papers use “protocol” and “algorithm” interchangeably, however it is important to distinguish them to understand the taxonomy of this field. In this section, we will introduce bio-inspired algorithms, how protocols leverage them, and the domains protocols are developed for.

2.1. Bio-Inspired Algorithms

Bio-inspired algorithms (BIA) are algorithms that mimic the behaviors, characteristics, and attributes of animals and insects to solve a range of problems. BIAs have a variety of problem-solving purposes, including optimization, routing (search/path optimization), clustering, localization, communication, sensing, and modeling [Kumar25]. BIAs on their own do not route packets the way protocols do, rather they provide the tools (search, optimization) for bio-inspired protocols to use. Examples of BIAs include Ant Colony Optimization (ACO), and Krill Herd (KH), which we will discuss in-depth later [Kumar25][Ananthi25]. For the sake of simplicity, schemes (collection of algorithms) will be considered BIAs in this paper.

2.2. Bio-Inspired Protocols

Bio-inspired protocols are a networking design that leverages BIAs to achieve an objective. Protocols govern how nodes communicate, defining message formats and packet-forwarding behaviors. Like BIAs, there are different types of protocols, including clustering and routing. Routing Protocols can be separated into many categories, each based on something else, and most of which are beyond the scope of this paper. Topology-based routing protocols can be further divided into Flat and Hierarchical/(Cluster-based) routing protocols [Beegum23]. Flat protocols, where networks can form from nodes without a hierarchy, can be categorized by routing strategies:

proactive, reactive (on-demand), and hybrid routing protocols. Reactive protocols initiate route discovery when a node has to deliver data packets, whereas proactive protocols maintain all routes in the network based on self-reporting by each node in the network to all other nodes, whereas hybrid routing combines both. To summarize, a bio-inspired protocol is designed around a strategy (proactive/reactive/hybrid). Bio-inspired algorithms are optimization/search methods used by the protocol to pick/manage routes, and the routing function (energy, reliability, delay) is the cost metric the BIA is optimizing for.

For example, one routing algorithm is Ant Colony Optimization-based Polymorphism Aware Routing (APAR). APAR integrates with ACO and is used within a reactive (on-demand) routing dynamic source routing (DSR) protocol. It uses pheromone concentration as its routing function, and has 3 phases: route exploration, route response and selection, and route maintenance. APAR is not a universal protocol, it is best fit for drones and UAV swarms, as it is highly adaptable. However, it has high routing overhead and moderate energy efficiency, which makes it unsuitable for low-energy battery operated devices, inefficient for cars in constrained environments, and unusable underwater. Each of these domains and constraints have their own network categories and associated protocols.

2.3. Infrastructure-less Networks (FANET, VANET, IoT, UWSN)

Bio-inspired protocols are essential for today's technological advancements. Vehicles, drones, sensors, and even your home thermostat, need to be able to communicate with other devices. These are examples of infrastructure-less wireless networks, of which there are three categories: Ad hoc, Wireless Mesh, and Wireless Sensor Network (WSN) [Beegum23]. Furthermore, there are three types of Ad hoc networks: flying ad-hoc network (FANET), vehicular ad-hoc network (VANET), mobile ad-hoc network (MANET). Technically, VANETs and FANETs are a subcategory of MANETs, and we will focus on these two subcategories. In this paper, however, we will discuss bio-inspired protocols in the context of 4 core domains: FANET, VANET, Internet of Things, and underwater wireless sensor network (UWSN).

FANETs are a collection of unmanned aerial vehicles (UAVs), such as drones, which need to communicate, cooperate, and/or act autonomously to achieve a task or goal, such as surveil traffic patterns, transport goods, and perform search and rescue missions [Agrawal25][Kumar25]. A VANET is a decentralized group of fast-moving cars, each acting as a node in a highly dynamic network. IoT is a broader concept, but it uses WSNs as a network of physical devices, equipped with sensors, software, and internet (public or private) capabilities to enable new ways to collect and exchange real world data. While IoT includes drones, underwater sensors, and cars, in this paper we will study these distinctly, and use IoT to represent other internet connected networks, such as smart homes and terrestrial sensor networks [Alabdulatif23]. UWSNs are a subcategory of WSNs, and are essential for the surveillance of marine life, monitoring of internet cables, and detection of natural phenomena such as earthquakes [Murali24]. These four categories differ greatly, in environments, applications, and challenges, which we will discuss in the next section.

Algorithms are problem-solving procedures, protocols use algorithms to calculate metrics for optimal path selection, nearest node to communicate with, and even the location of the node itself, such that they can share this information with other nodes in the network, according to a set of

rules that is most optimal for the environment they are operating in. To study the algorithms and protocols themselves, we must understand the motivation behind them, specifically, what problems are they solving.

3. Key Challenges

Each network domain, operating in its own environment, faces environment specific challenges. These challenges motivate the study of nature's pre-existing solutions, and the development of protocols based on these solutions. The following subsections will discuss challenges faced in these networks, which will then motivate our discussion of the solutions (protocols) in section 4.

3.1. FANET

FANETs face some of the steepest challenges in networking design. FANET protocols need to be able to handle the highest speeds (0–100 m/s), with full freedom of mobility, and rapid topology changes (drones dropping and joining swarms). Furthermore, FANETs have high power consumption, sparse node density, and are far above the ground. Their mobility model is often predetermined, but autonomous UAVs are semi-random, which motivates the study of swarm intelligence. The communication range requires large coverage, and the frequency is 5 GHz between UAVs and 2.4 GHz between the ground station [Beegum23].

3.2. VANET

VANETs have lower speeds than FANET (20–30 m/s on highways, 6–10 m/s otherwise), and topology changes depend on traffic. Their power consumption is low, and they have a high density of nodes. Their radio propagation is close to the ground, and their mobility model is predictable. Their communication range is small and they operate on a 5.9 GHz frequency [Beegum23].

3.3. IoT

As a more general concept, IoT will need to be compared slightly differently. IoT devices are always connected to the internet, and therefore require heightened security. They must be interoperable, with compatible and standardized protocols between various kinds of devices. Scalability is a challenge, from coordinating devices to managing data flows. Like FANETs, energy constraints are a key concern, as most devices are small and/or battery powered, and need to be able to operate without human intervention for extended time. Due to these constraints, tradeoffs must be made between data collection, storage, and transmission, while keeping power in mind. Furthermore, their low power and emphasis on scale means frequent topology changes, often less so than FANET, but it depends on the environment/use-case/devices being used [Ahmed24][Alabdulatif23]. The very nature of being internet connected requires security considerations, which is frequently under-prioritized in bio-inspired protocols.

3.4. UWSNs

Due to their underwater nature, UWSNs face a number of unique challenges. Water currents, temperature, pressure, animals, and salinity all pose obstacles when developing protocols. The currents at sea move and dislocate sensors, causing energy loss, topology changes, and require power hungry localization techniques and sensors to keep networks connected, and often result in significant localization errors. Furthermore, optical signals are scattered underwater, and the acoustic channel has limited bandwidth. Like in FANETs and IoT, sensors are typically battery powered, so acoustic communication protocols face low power, elevated noise levels, high energy attenuation, and long propagation delays with high error rates and distortion. UWSNs are sparse with limited anchor nodes and uneven, dynamic node distribution [Murali24].

FANETs, VANETs, and UWSNs all exist in distinct environments, all which pose unique challenges, and thus require unique protocols designed specifically for their constraints. While IoT is not delegated to a specific environment, it is nonetheless essential for the comprehensiveness of our survey. The protocols that govern communication between high velocity drone swarms, cars on the highway, and underwater sensors facing rough waves would be unpractical and inefficient in the context of your smart home or business. In the next section, we will survey several protocols and their distinguishing attributes.

4. Swarm Coordination and Adaptive Routing

Swarm coordination, or swarm intelligence (SI), is a field of study to enable protocols to facilitate the decentralized self-coordination of nodes in a network, often mimicking the flocking patterns of birds, schools of fish, or patterns of insects like ants and glowworms. It is essential in all 4 domains that we presented in this paper. FANETs, VANETs, IoT, and UWSNs all require coordination and communication between network members. Adaptive routing is an essential part of bio-inspired protocols, as all 4 domains experience extreme variables where adaptability is a key trait needed for reliable networks. Swarm coordination and adaptive routing are not mutually exclusive traits, and we will see how protocols leverage both to achieve their goals [Kumar25].

4.1. Problem Scope and Metrics

Swarm coordination protocols leverage SI-based BIA's to solve problems regarding routing, formations/clustering, consensus, and dividing work, all with high frequencies of topology changes and energy constraints. Metrics for swarm-based protocols measure convergence time, coverage percent, control/message overhead, energy cost, topology change rate, scalability (density), and safety (security) [Kumar25][Ananthi25]. The goal of adaptive routing is to deliver packets end-to-end under high levels of mobility, with intermittent links, energy constraints, and topology changes. Metrics include packet delivery ratio (PDR), end-to-end delay, control overhead, route recovery, scalability, and security [Kumar25].

4.2. Mechanism Taxonomy in Bio-Inspired Algorithms

Mechanisms used by BIAs include stigmergy, which is coordination through marking, and a prominent example of this is how ants leave pheromones for other ants to follow paths, optimizing food sourcing by prioritizing stronger pheromones, while weak pheromones dissipate [Beegum23]. This mechanism is a prominent feature of almost all ant-based algorithms, namely ACO and Ant Colony Routing (ACR). ACR, an application of the ACO metaheuristic, is a VANET routing algorithm that uses Route Explorer Ants (REANTs) and Route Manage Ants (RMANTs) to discover efficient and secure communication paths based on pheromone levels [Ramamoorthy24].

Glowworm swarm optimization (GSO) uses residual energy levels and luciferin levels (brightness means better position) to perform efficient cluster head (CH) election for cluster routing and management [Kumar25]. Particle Swarm Optimization (PSO) can be used to optimize routing path generation. It is dynamic, provides very high throughput, prompts convergence, and reduces energy consumption. The BIA is optimized using residual energy, distance, and number of nodes in a path [Ahmed24]. Butterfly Optimization Algorithm (BOA) is a highly stable clustering algorithm that mimics the mating behaviors of butterflies, which use a fragrance to share information amongst each other. The search mechanism of BOA is divided into two parts: global and local exploration. Local exploration is characterized by butterflies following a random walk, spreading fragrance to find mates. When a butterfly detects a fragrance of another butterfly, it will move toward it, which is known as global search [Ahmed24]. Bee's waggle dance is a method of communication by honey bees that creates coded messages for distance and direction of food sources for the hive [Kumar25]. We will now review protocols that leverage these BIAs and mechanisms.

4.3. Protocols and Analysis

In IoT-enabled UWSNs, it is essential to establish reliable data transmission paths between underwater nodes. Hybrid Optimization-based Cooperative Opportunistic Routing (HOCOR) leverages PSO and genetic algorithms (GA) to compute metrics such as packet collisions, distance, connection strength, transmission capabilities, and remaining energy to enable reliable communication between nodes and the surface sink [Murali24]. In IoT, Bio-Inspired energy-efficient Cluster and Routing (BICR) protocol leverages a hybrid BOA-PSO method to improve network lifetime in disaster scenarios. BICR uses an improved BOA to increase network lifetime and improve connectivity by minimizing energy consumption when nodes communicate with the sink. BOA handles cluster formation, while PSO increases network lifetime by optimizing the routing path generation [Ahmed24].

Bio-inspired clustering scheme for FANETS (BICSF) is a clustering-based routing scheme which leverages GSO and Krill Herd (KH) to form clusters (broadcast GSO-computed fitness value), elect cluster heads (UAV with maximum fitness value), manage cluster topology through the exchange of control messages inspired by Krill Swarming patterns, and finally select routes based on the remaining energy and neighbor density [Kumar25]. In VANETs, ants are a strong inspiration. Reliable route discovery by using ant colony optimization (RDACO) is a protocol that uses ACO as a forwarding strategy to find a stable route with minimum delay, optimizing for

quality of service (QoS). This characteristic of ACO makes it both a swarm algorithm and an adaptive routing algorithm. RDACO handles the message formats and how “ants” are sent, while ACO handles the pheromone computations, and ant-based search/selection [Ramamoorthy22]. Enhanced Location-Aided Ant Colony Routing (ELAACR) is a two-phase protocol that uses Location-Aided Key Management (LAKM) and ACR to offer secure communication between vehicles. LAKM is a scheme that uses a group signature concept to ensure network security, and ACR uses stigmergy to find efficient, and secure shortest paths for communication [Ramamoorthy24]. BeeAdHoc is a swarm based adaptive routing protocol, which mimics the foraging behavior of honey bees for efficient data routing. It is an on-demand (reactive) routing and is best suited for FANET, performing well regarding throughput and overhead [Beegum23]. BeeAdHoc exchanges two types of messages frequently: scouts and foragers. Scouts search on-demand for new paths, foward scounts are messages from the source node via broadcast. Backward scouts are sent by the destination when it recieves the forward scout message, which retraces the steps. Final route is selected via bee waggle dance, which evaluates the number of UAVs needed for path coverage. Foragers recieve data packages from packer agents on the "dance floor", and then aqcuire routess from scouts or another forager to transmit the data on the multihop connection. When foragers return from the destination, they perform a "dance" on the dance floor to recruit more foragers [Kumar25].

Looking at Table 1, it is evident that the study of bio-inspired protocols cannot exist purely in the vacuum of a single domain. It is not required for FANET-optimized protocols to look only to birds and flying insects for solutions, as BICSF is inspired by the mating patterns between flightless female glowworms and flying male glowworms, as well as the herding patterns of Krill, which one would expect to apply to UWSNs. Furthermore, IoT, a more general category, features protocols that leverage the mating patterns of butterflies. Ultimately, inspiration for protocols is not domain restricted, and thus survey papers should not be limited to protocols within a single domain. Section 4 introduced just a small number protocols and algorithms from the vast and growing field of bio-inspired protocols. Table 1 provides a concise and comparative view at what makes each protocol unique, and most importantly, what makes them optimal for their domain, even when the underlying biological inspiration exists in a different one.

5. Summary

Bio-inspired protocols are protocols that leverage nature’s solutions to solve the problems in our networks. Bio-inspired protocols enable decentralized communication in harsh and variable environments, from the sky to the sea. Bio-inspired algorithms are the mechanisms used by protocols which mimic animal and insect behaviors, such as ants, birds, and fish, to find optimal clusters, paths, and formations. Swarm coordination and adaptive routing are overlapping attributes found in these algorithms, enabling networks to be resilient when faced with sparse, high mobility, and underwater networks, and are measured by convergence speeds, overhead, power consumption and more. Prominant algorithms and protocols are presented in Section 4, and Table 1 provides a comparative analysis of different protocols across domains. Protocols are compared by adaptability, link stability, energy efficiency, scalability, and more. Security is often overlooked in the development of bio-inspired protocols, but is essential to all domains, and is an import area of study for the future.

Table 1. Bio-inspired swarm coordination and adaptive routing protocols

Protocol	Strategy	Bio-inspired algorithm(s)	Key function(s) / how it works	Domain(s) where it excels	Adapt-ability	Link stability	Multiple routes	Energy efficiency	Overhead	Scalability	Security
BICSF	Clustering (hierarchical routing)	GSO + KH	Forms energy-aware clusters, uses luciferin value and residual energy for CH election and cluster maintenance, routes via CHs	FANET (UAV swarms)	Yes	Low	No	Yes	High	High	No
BeeAdHoc	Swarm intelligence–based on-demand reactive routing	Bee's waggle dance	Uses foward scouting phase (broadcast, multihop) to find destination, destination responds with backward scout, both track residual energy and hop count. Route selection uses bee waggle dance formula for coverage calculation, and then foraging messages are sent with data packages.	FANET / MANET-like ad hoc networks (can be adapted to VANET)	Yes	Low	Yes	Yes	Computationally High, Mod. Communication	Low	No
APAR	On-demand reactive, swarm-based multi-path routing	ACO + DSR	Uses stigmergy (distance, congestion, route stability) to discover and select routes on demand; maintains multiple candidate paths	FANET (ad hoc UAV networks)	Yes	Low	Yes	Mod.	High	High	No

Table 1. Bio-inspired swarm coordination and adaptive routing protocols

Protocol	Strategy	Bio-inspired algorithm(s)	Key function(s) / how it works	Domain(s) where it excels	Adapt-ability	Link stability	Multiple routes	Energy efficiency	Overhead	Scalability	Security
RDACO	QoS-aware on-demand reactive routing	ACO	Discovers multiple candidate paths and selects those with high stability and low delay to improve PDR in variable traffic conditions	VANET (highway & urban)	Yes	High	Yes	Mod.	High	Mod.	No
EL-AACR	Secure location-aided on-demand reactive routing	ACR + LAKM	Combines ACR with location-aided key management to authenticates nodes and establishes resliant and secure routes	VANET (secure vehicular communication)	Yes	High	Yes	Mod.	High	Mod.	Yes
BICR	Cluster-based multi-hop routing for IoT WSNs	Hybrid BOA-PSO (Butterfly Optimization Algorithm for clustering, PSO for routing)	Selects CHs and routes using residual energy, distance to sink, and coverage; maximizes lifetime & throughput, reduces packet drops in disaster scenarios	IoT WSN (disaster monitoring)	Yes	Mod.	No	High	Mod.	High	No
HOCOR	Cooperative opportunistic routing (swarm-intelligence)	Hybrid Genetic Algorithm (GA) + PSO	Uses GA-PSO relay selection (distance, collision probability, link quality, residual energy) to build cooperative opportunistic paths	IoT-enabled UWSN	Yes	High	Yes	High	High	Mod.	No

List of Acronyms

- ACO – Ant Colony Optimization
- ACR – Ant Colony Routing
- APAR – Ant Colony Optimization–based Polymorphism Aware Routing
- BIA – Bio-Inspired Algorithm
- BICR – Bio-Inspired energy-efficient Cluster and Routing
- BICSF – Bio-Inspired Clustering Scheme for FANETs
- CH – Cluster Head
- DSR – Dynamic Source Routing
- ELAACR – Enhanced Location-Aided Ant Colony Routing
- FANET – Flying Ad hoc Network
- GA – Genetic Algorithm
- GSO – Glowworm Swarm Optimization
- HOCOR – Hybrid Optimization-based Cooperative Opportunistic Routing
- IoT – Internet of Things
- KH – Krill Herd
- LAKM – Location-Aided Key Management
- MANET – Mobile Ad hoc Network
- PDR – Packet Delivery Ratio
- PSO – Particle Swarm Optimization
- RDACO – Reliable Route Discovery using Ant Colony Optimization
- SI – Swarm Intelligence
- UAV – Unmanned Aerial Vehicle
- UWSN – Underwater Wireless Sensor Network
- VANET – Vehicular Ad hoc Network
- WSN – Wireless Sensor Network

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