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Comprehensive Literature Review on Bio Inspired Optimization-based Path Selection for Message Forwarding in Delay Tolerant Network

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***Abstract*— Delay Tolerant Network (DTN) is suitable to work in extreme conditions where traditional networks failed to establish path between nodes, this paper seeks to offer a thorough examination of the use of bio-inspired optimization methods for path selection and message forwarding in DTNs. The paper examines the efficacy of three algorithms Genetic Algorithms (GA), Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO) in improving message forwarding in difficult DTN environments with erratic delays and sporadic connectivity. By means of a thorough examination of existing literature and practical trials employing actual DTN traces, the study unveils noteworthy advancements attained by bio-inspired optimization techniques. In terms of resource usage, adaptability to changing network conditions, and message delivery efficiency, GA, ACO, and PSO show encouraging outcomes. The comparison study clarifies the advantages and disadvantages of each method, providing practitioners, researchers, and network designers with insightful information. The study's practical significance is further enhanced by the validation of these bio-inspired methodologies using real-world DTN traces, which serves as a link between theoretical developments and practical application. This paper provides a practical guide for using bio-inspired optimization in DTNs by identifying optimal configurations and recommended practices. The results have broad implications for a variety of scenarios, such as disaster recovery, communication in space, and remote locations.**

***Index Terms* - Delay-Tolerant Networks (DTNs), Bio-Inspired Optimization, Genetic Algorithms (GA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Message Forwarding, Network Resilience.**

I. INTRODUCTION

The development of Delay Tolerant Networks (DTNs) has introduced a novel networking paradigm aimed at enabling effective communication in demanding settings characterized by dynamic topologies, significant latency, and intermittent connectivity. The advent of Delay-Tolerant Networks (DTNs) represents a divergence from conventional networking methodologies, prompting the investigation of novel techniques to effectively tackle the unique issues posed by these dynamic settings [1],[2],[3],[4],[5].

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A. Evolution of Networking Paradigms

The traditional networking architecture, which was initially designed for stable environments with regular connectivity, has inherent drawbacks when used in situations where connectivity is unexpected and intermittent. Academic researchers are presently directing their attention towards the advancement of networks that exhibit adaptability in the face of difficult conditions, including remote geographical areas, regions affected by calamities, and communication in extraterrestrial environments.

These specific situations require communication systems that possess inherent resilience. The recognition of the need for novel techniques to overcome communication issues in contexts with delays led to the birth of Delay-Tolerant Networks (DTNs), marking a significant shift in perspective. The seminal contribution made [5], titled "A delay-tolerant network architecture for challenged internets"[5], laid the foundation for the development of Delay-Tolerant Networks (DTNs).

This seminal study provided evidence of the insufficiency of traditional networking topologies in scenarios characterized by numerous network partitions and significantly prolonged delay paths. The suggested architectural framework presents novel layers that integrate wireless sensor networks (WSNs), packet forwarding networks (PFN), and end-to-end services, thereby establishing a foundation for future investigations in this dynamic domain [1],[2],[3],[4],[5].

B. Bio-Inspired Optimization in DTNs

The limitations of traditional algorithms in adapting to the dynamic nature of DTNs led researchers to explore bio-inspired optimization techniques. These methods take inspiration from natural processes, mimicking evolutionary principles observed in biological systems. The integration of bio-inspired algorithms in DTNs addresses the need for adaptability, self-organization, and efficiency in the face of challenging conditions.

The research [1], titled "Online Algorithms for Adaptive Optimization in Heterogeneous Delay Tolerant Networks"[1], exemplifies the application of bio-inspired optimization. The study introduces a multi-dimensional stochastic approximation algorithm that adapts to the network's heterogeneous state and node capabilities. This adaptive algorithm optimizes the probability of delivering messages, showcasing the potential of bio-inspired strategies in heterogeneous DTNs.

C. Physical Deployment Optimization

Optimizing the physical deployment of relay nodes in DTNs is crucial for enhancing communication opportunities and overall network efficiency. [2] Work on the "Optimization of Throw Box Deployment in Delay Tolerant Network" addressed the strategic placement of intermediate relay nodes, referred to as throw boxes. Employing evolutionary algorithms, the study sought to find optimal locations for throw boxes, maximizing coverage, minimizing average delay, and improving the overall delivery ratio. This work underscores the versatility of bio-inspired optimization, extending beyond traditional routing approaches to encompass physical configuration for improved communication outcomes.

D. Social-Aware Routing Strategies

Recognizing the social dynamics among nodes within a network, [3] Proposed a routing scheme based on nodes' sociality. This approach integrates social network analysis techniques to identify nodes with higher social influence, assigning them priority in routing decisions. By reducing conflicts and fostering cooperation among nodes, the authors asserted that their social-aware routing strategy enhances overall network performance. This reference highlights the potential of bio-inspired optimization to leverage principles from natural systems to improve routing efficiency in DTNs.

E. Feature Selection and Swarm Intelligence

The incorporation of swarm intelligence in bio-inspired optimization techniques gained prominence in addressing challenges across different layers of the networking stack. [4] Work on "Bio-Inspired Feature Selection: An Improved Binary Particle Swarm Optimization Approach" presented an enhanced version of binary particle swarm optimization (BPSO). By incorporating diversity and inertia features, the authors aimed to improve BPSO's ability to explore diverse regions of the search space, thereby escaping local optima. Applied to feature selection, this approach showcased the versatility of swarm intelligence in enhancing classification in machine learning, signaling its potential applications in network optimization. As we navigate through the diverse landscape of bio-inspired optimization in DTNs, the collective insights from these references provide a foundational understanding of how these approaches have evolved to address specific challenges. The historical progression from conventional networking paradigms to bio-inspired strategies underscores the necessity for adaptive and unconventional solutions in dynamic and challenging communication environments [4],[5],[6],[7],[8], [9], [10].

F. Current Trends and Emerging Paradigms

The contemporary landscape of DTNs witnesses an amalgamation of bio-inspired optimization with emerging paradigms, such as Software-Defined Networking (SDN). [9] Work on the "End-to-End Delay Minimization-Based Joint Rule Caching and Flow Forwarding Algorithm for SDN" exemplifies this convergence. The paper introduces a joint design of rule caching and flow forwarding strategies for multiple user flows within an SDN framework. By formulating an end-to-end delay minimization problem and proposing a heuristic algorithm, the authors showcase the adaptability of bio-inspired optimization within the dynamic SDN architecture.

G. Application-specific Optimization

Considering the energy constraints in certain scenarios, [7] investigation into "Energy-Aware Forwarding Strategies for Delay Tolerant Network Routing Protocols" adds another layer of specificity to bio-inspired optimization. Focused on wildlife tracking applications, where sensors on animals transmit data to base stations, the study proposes three energy-aware routing protocol strategies. These strategies consider the available energy efficiently for transmission and sensing, enhancing packet delivery rates by up to 13%. This application-specific optimization highlights the adaptability of bio-inspired techniques to diverse scenarios within DTNs [10],[11],[12],[13],[14],[15],[16],[17],[18], [19].

H. Collaborative Cache Strategies

The latest trend in optimizing network paths through collaborative cache methods introduces a collaborative approach to enhance routing efficiency. This strategy identifies data-sharing methods and optimizes subsets of paths between source and destination nodes. The collaborative cache approach aims to improve standard metrics such as cost, transmission speed, and network traffic conditions. The reported benefits, including a 20% reduction in the distance between nodes, a 15% decrease in path identification time, and a nearly 50% reduction in cache allocation demand, reflect the current focus on collaborative optimization strategies in DTNs [19], [20], [21], [22], [23], [24], [25].

In summary, the journey from traditional networking paradigms to bio-inspired optimization in DTNs reveals a narrative of adaptation and innovation. The references discussed illustrate the evolution of strategies, encompassing adaptive algorithms, physical deployment optimization, social-aware routing, swarm intelligence, and the integration of bio-inspired techniques with emerging paradigms. As we delve deeper into each reference, we will unravel the intricate methodologies and contributions that collectively define the trajectory of bio-inspired optimization in the evolving landscape of DTNs.

II. LITERATURE SURVEY

The application of bio-inspired optimization approaches for path selection has received a lot of attention in the context of Delay-Tolerant Networks (DTNs), where intermittent connectivity poses issues. This overview of the literature examines the body of research and groups the studies into important subtopics to provide readers a thorough grasp of the developments in bio-inspired message forwarding in DTNs.

A. Introduction to Delay Tolerant Networks (DTNs)

It is essential to comprehend the basic ideas behind DTNs in order to investigate optimization strategies. Because DTNs have sporadic connectivity, standard routing is difficult. Path selection becomes crucial in this situation, impacting network performance and message delivery [1],[2],[3],[4],[5].

B. Challenges in Delay Tolerant Networks

Due to their dynamic and unexpected characteristics, which include fluctuating node mobility, lengthy delays, and intermittent connectivity, delay-tolerant networks (DTNs) provide a special set of difficulties. Comprehending these obstacles is essential for the efficient development and enhancement of communication protocols in DTNs [15],[16],[17],[18],[19], [20].

Intermittent Connectivity

- Description: DTNs frequently function in settings where nodes disconnect frequently, which makes it difficult to create end-to-end communication channels.
- Impact: Specialized solutions are needed to manage intermittent connectivity because traditional routing algorithms, which are meant for networks with continuous connectivity, are insufficient.

Variable Node Mobility

- Description: Nodes in DTNs, like mobile phones or sensor nodes, move in a variety of ways, which can result in chance meetings and few opportunities for face-to-face interaction.
- Impact: As nodes' movements affect the establishment and upkeep of communication routes, efficient routing becomes more complicated. It's possible that static routing assumptions don't apply.

Long Delays

- Description: Messages in DTNs may experience prolonged delays before reaching their destination due to intermittent connectivity and the need to opportunistically relay through encounter-based communication.
- Impact: Delays can affect the timely delivery of critical information, making it essential to develop routing strategies that consider and mitigate these delays.

Limited Network Resources

- Description: DTNs often operate in resource-constrained environments, where nodes have limitations in terms of energy, bandwidth, and storage capacity.
- Impact: Routing protocols must optimize resource usage, considering energy-efficient strategies and minimizing the overhead associated with storing and forwarding messages.

Security and Privacy Concerns

- Description: In DTNs, nodes may be untrusted, and the lack of a continuous communication path raises security and privacy challenges in message forwarding and storage.
- Impact: Ensuring the confidentiality and integrity of messages while considering the privacy of users becomes paramount, requiring the development of secure communication protocols.

Heterogeneous Node Types

- Description: DTNs often comprise various types of nodes, such as smartphones, laptops, and sensors, each with different capabilities and communication ranges.
- Impact: Designing routing protocols that can adapt to the heterogeneity of nodes is crucial to achieving efficient message delivery across the diverse set of devices.

Scalability Issues

- Description: As the number of nodes in a DTN increases, scalability becomes a concern, particularly in terms of message routing and efficient resource utilization.
- Impact: Scalability issues can hinder the effectiveness of communication protocols, requiring the development of scalable algorithms that can handle larger and more complex DTN scenarios.

Addressing these challenges requires innovative approaches in protocol design, including the integration of bio-inspired optimization techniques, as observed in the literature.

By understanding and mitigating these challenges, researchers can contribute to the development of robust and efficient communication solutions for DTNs, fostering applications in remote and challenging environments where traditional networks fall short.

C. Bio-Inspired Optimization Techniques

Bio-inspired optimization techniques leverage principles from nature to develop algorithms that can solve complex problems. In the context of Delay Tolerant Networks (DTNs), where traditional routing approaches face challenges due to intermittent connectivity, bio-inspired methods offer innovative solutions. This section delves into three prominent bio-inspired optimization techniques applied to path selection in DTNs [2],[3],[4],[5],[6], [7], [8].

Genetic Algorithms (GAs) in DTNs

- GAs are inspired by the natural selection and genetics. In the context of DTNs, GAs have been employed to optimize path selection by treating potential paths as candidate solutions subject to evolution. The fundamental components of GAs, such as crossover, mutation, and selection, are adapted to represent the dynamic nature of network paths.
- Research studies have explored the effectiveness of GAs in optimizing the probability of delivering messages in heterogeneous DTNs composed of different node types. The multi-dimensional stochastic approximation algorithm, inspired by GAs, adapts to the changing network state and node capabilities without requiring full information.

  Comparative analyses demonstrate the algorithm's ability to achieve optimal performance at runtime, outperforming existing methods in terms of convergence and stability.

Ant Colony Optimization (ACO) for Routing

- Ant Colony Optimization is inspired by the foraging behavior of ants, where pheromone trails guide them to discover optimal paths. In the context of DTNs, ACO has been applied to enhance routing by allowing nodes to mimic ant-like behavior. Nodes deposit virtual pheromones on paths, influencing the routing decisions of other nodes.
- The literature highlights instances where ACO has shown promise in optimizing routes in DTNs. The routing scheme proposed based on nodes' sociality utilizes social network analysis to identify socially influential nodes, assigning them higher priority for routing decisions. This approach aims to improve network performance by reducing conflicts and fostering cooperation among nodes.

Particle Swarm Optimization (PSO) for Network Optimization:

- Particle Swarm Optimization is inspired by the collective movement of bird flocks and fish schools. In the context of DTNs, PSO has been explored to optimize network parameters dynamically. PSO involves particles (representing potential solutions) moving through the solution space to find optimal solutions.
  - The literature[3] introduces an improved version of Binary Particle Swarm Optimization (BPSO) for feature selection in machine learning. While not directly applied to path selection, this example illustrates the adaptability of PSO to different optimization problems. The modified BPSO incorporates diversity and inertia features, enhancing its ability to explore different regions of the search space and escape local optima.

D. Conclusion of Bio-Inspired Optimization Techniques

Bio-inspired optimization techniques bring a unique perspective to path selection in DTNs. Genetic Algorithms, Ant Colony Optimization, and Particle Swarm Optimization offer adaptive and evolutionary approaches that align with the dynamic and intermittent nature of DTNs. These techniques, as demonstrated in the literature, contribute to enhancing the efficiency and adaptability of path selection in challenging network environments.
The next sections of the review will delve into comparative analyses, real-world applications, and emerging trends in bio-inspired DTN optimization.

E. Comparative Analysis of Bio-Inspired Approaches

The three main bio-inspired optimization methods used for path selection in Delay Tolerant Networks (DTNs) are compared in this part.

Genetic Algorithms (GAs)

Genetic Algorithms mimic the process of natural selection to evolve solutions to optimization problems. In the context of DTNs, GAs have shown effectiveness in adapting to heterogeneous networks composed of diverse node types, such as mobile phones, laptops, and sensors.

Strengths

- Adaptability: GAs adapt to the changing network state and node capabilities without requiring complete information.
- Optimal Performance: The multi-dimensional stochastic approximation algorithm inspired by GAs achieves optimal performance at runtime, outperforming existing methods in convergence and stability.

Limitations

- Computational Overhead: The computational complexity of GAs may pose challenges in resource-constrained DTN nodes.
- Dependence on Parameters: GAs' performance can be sensitive to parameter settings, requiring careful tuning.

Ant Colony Optimization (ACO)

Ant Colony Optimization is inspired by the foraging behavior of ants, where virtual pheromone trails guide the discovery of optimal paths. In DTNs, ACO has been applied to enhance routing decisions by allowing nodes to mimic ant-like behavior[2].

Strengths

- Decentralized Decision-Making: ACO fosters decentralized decision-making, aligning with the nature of DTNs.
- Path Optimization: ACO can optimize routes dynamically by leveraging virtual pheromones.

Limitations

- Sensitivity to Parameters: ACO's performance may be influenced by the proper tuning of parameters.

- Scalability Challenges: As the network scales, maintaining pheromone information for all paths can become resource-intensive.

Particle Swarm Optimization (PSO)
Particle Swarm Optimization draws inspiration from collective movement in nature, such as bird flocking. In the context of DTNs, PSO has demonstrated adaptability in optimizing various network parameters[3].
Strengths
- Adaptive Exploration: PSO facilitates adaptive exploration of the solution space, improving the chances of finding optimal paths.
- Real-Time Adaptation: PSO can adapt in real-time to changing network conditions.

Limitations
- Global Exploration Challenge: PSO may face challenges in globally exploring the solution space, potentially converging to local optima.
- Parameter Sensitivity: Like other bio-inspired techniques, the performance of PSO can be sensitive to parameter settings.

F. Comparative Analysis

Each bio-inspired approach brings unique strengths and limitations to the context of DTN path selection. GAs offer adaptability and optimal performance but may face computational overhead. ACO provides decentralized decision-making and path optimization but may require careful parameter tuning. PSO excels in adaptive exploration and real-time adaptation but may encounter challenges in global exploration.
Choosing the most suitable approach depends on the specific characteristics and requirements of the DTN environment. Future research directions could focus on hybrid approaches that leverage the strengths of multiple bio-inspired techniques to further enhance the robustness and efficiency of path selection in DTNs.

G. Real-world Applications and Case Studies

The application of bio-inspired optimization techniques for path selection in Delay Tolerant Networks (DTNs) has gained significant attention due to its potential in addressing communication challenges in various real-world scenarios. “Online Algorithms for Adaptive Optimization” [1]. proposed a multi-dimensional stochastic approximation algorithm for adaptive optimization in heterogeneous DTNs. Their work focuses on optimizing the probability of delivering messages among different node types without requiring full information. The algorithm adapts to network states and node capabilities, showcasing the potential of online algorithms in dynamic DTN environments.
“Optimization of Throw Box Deployment”: [2] addressed the deployment of throw boxes, intermediate relay nodes in DTNs. Employing an evolutionary algorithm, their study optimizes the locations of throw boxes to maximize coverage, minimize average delay, and enhance the delivery ratio. This research highlights the significance of optimizing network infrastructure for efficient message forwarding.
“Routing Based on Nodes Sociality”: [3] proposed a routing scheme considering nodes' sociality. Utilizing social network analysis, their approach assigns higher priority to socially connected nodes, reducing conflicts and fostering cooperation. This sociality-based routing provides insights into improving message delivery efficiency in socially influenced DTN environments.
“Bio-Inspired Feature Selection”: [4]. introduced a binary particle swarm optimization approach for feature selection. Although not directly focused on DTNs, this work contributes insights into bio-inspired optimization. Feature selection is a crucial aspect in DTNs, and this paper provides a broader perspective on bio-inspired optimization's effectiveness in solving optimization problems.
“DTN Architecture for Challenged Internets”: Kevin Fall proposed a DTN architecture for challenged internets in 2003 [5]. While not specifically focusing on bio-inspired optimization, this foundational work addresses challenges posed by limited resources in network nodes. Understanding the architecture is essential as it lays the groundwork for subsequent optimization techniques.
“Experimental Results of Conditional Shortest Path Routing”: [6] presented experimental results for conditional shortest path routing in DTNs. By introducing a novel metric called conditional intermeeting time, the study explores improvements in routing by minimizing intermeeting times. This work adds a dimension to path selection strategies, enhancing traditional shortest path routing.
“Energy-Aware Forwarding Strategies”: [7]. proposed energy-aware forwarding strategies for DTN routing protocol. Considering energy constraints, their work enhances existing routing protocols by incorporating energy considerations, crucial for optimizing message forwarding in resource-constrained environments.

“End-to-End Delay Minimization-Based Joint Rule Caching and Flow Forwarding Algorithm for SDN”: [9] proposed an end-to-end delay minimization-based algorithm for Software-Defined Networking (SDN). Although SDN differs from DTNs, the joint rule caching and flow forwarding approach can inspire solutions for efficient message forwarding in dynamic network environments.

“Feedback-Based Probability Selection for Frame Forwarding in AVB Switched Ethernet”: [10] introduced a feedback-based probability selection for frame forwarding in Audio Video Bridging (AVB) switched Ethernet. While not directly related to DTNs, the feedback-based approach is crucial for real-time content delivery, providing insights into optimizing forwarding strategies.

“Location-Aware Waypoint-Based Routing for Airborne DTNs”: [11] proposed a location-aware waypoint-based routing protocol for airborne DTNs in search and rescue scenarios.

By leveraging geographical information of UAVs, this work provides a directional approach to optimize message forwarding in aerial DTNs.

“Bio-Inspired Clustering Scheme for FANETs”: [12] presented a bio-inspired clustering scheme for Flying Ad Hoc Networks (FANETs). Using a hybrid mechanism of glowworm swarm optimization and krill herd algorithms, the study optimizes clustering for efficient message forwarding in mobile airborne networks.

“Bio-Inspired Routing Algorithm Based on ACO for WSNs”: [13] proposed a bio-inspired routing algorithm based on Ant Colony Optimization (ACO) for Wireless Sensor Networks (WSNs)[13]. Although not directly related to DTNs, the ACO-based algorithm provides insights into leveraging swarm intelligence for optimizing message forwarding in resource-constrained networks.

“Routing Optimization for DTNs in Rural Applications”: [16] addressed routing optimization for DTNs in rural applications using a distributed algorithm. Considering scenarios with limited Internet access, this work emphasizes the importance of optimizing routing algorithms for effective message delivery in challenging environments.

“Grid-Based Bio-Inspired Energy Efficient Trusted Hybrid Routing Protocol for MANET”: [15] proposed a grid-based bio-inspired energy-efficient trusted hybrid routing protocol for Mobile Ad Hoc Networks (MANETs). The gCMOGAEETN algorithm utilizes grid clusters and multi-objective genetic algorithms for optimal route discovery, providing insights into energy-efficient routing strategies.

The literature review encapsulates diverse research contributions in the domain of bio-inspired optimization for path selection in Delay-Tolerant Networks. The surveyed papers encompass various aspects, from optimizing network infrastructure and routing strategies to considering energy constraints and social aspects of nodes. Each study provides valuable insights into the challenges and opportunities associated with forwarding messages in DTNs, contributing to the broader understanding of bio-inspired optimization methods in dynamic and resource-constrained networking environments.

H. Hybrid Approaches in Bio-Inspired Optimization

In bio-inspired optimization, hybridization is the process of fusing components from several algorithms to produce fresh strategies that capitalize on the advantages of each one. Hybrid techniques provide better performance and flexibility when it comes to path selection for forwarding in Delay Tolerant Networks (DTNs). The many hybridization techniques used in bio-inspired optimization with DTNs are examined in this section [28-35].

Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO)

By combining PSO with ACO, a hybrid strategy is introduced that takes advantage of both ACO's path-building skills and PSO's exploration-exploitation balance. ACO concentrates on pheromone-based path selection, whereas PSO considers both personal and global optimal solutions when determining particle movement. The combination of these techniques improves path selection and convergence in DTNs.

Genetic Algorithms (GA) and Swarm Intelligence

Inspired by the collective behavior found in nature, GA and swarm intelligence are combined to produce a hybrid model that maximizes message forwarding. GA provides the evolutionary aspect, exploring solution spaces through crossover and mutation, while swarm intelligence ensures decentralized decision-making, mimicking social behavior in groups. This hybridization aims to enhance adaptability to dynamic DTN environments.

Binary Particle Swarm Optimization (BPSO) and Genetic Algorithms (GA)

Hybridizing BPSO with GA introduces a mechanism that combines the binary representation of BPSO with the evolutionary principles of GA. This hybrid approach enhances the diversity and exploration capabilities of

BPSO, mitigating the risk of premature convergence. The binary encoding in BPSO is preserved, contributing to effective feature selection in bio-inspired optimization scenarios.

Glowworm Swarm Optimization (GSO) and Krill Herd (KH)
In the context of Flying Ad Hoc Networks (FANETs), a hybrid clustering scheme involves integrating GSO and KH algorithms. GSO mimics glowworm behavior for forming clusters, while KH introduces genetic operators for optimizing cluster structure. This hybridization enhances the efficiency of cluster formation, optimizing energy-aware communication among UAVs.

Ant Colony Optimization (ACO) and Wireless Sensor Networks (WSNs):
Applying ACO to optimize routing in Wireless Sensor Networks involves a hybrid approach tailored for specific constraints in sensor network environments. ACO, inspired by ant foraging behavior, is adapted to consider node mobility, energy levels, and network topology. This hybridization aims to improve routing efficiency in WSNs, contributing to enhanced message delivery in DTNs.

Grid Clusters and Multi-Objective Genetic Algorithms (MOGA)
The integration of grid-based clusters with MOGA in routing protocols for Mobile Ad Hoc Networks (MANETs) introduces a hybrid paradigm. Grid clusters provide a structured approach, and MOGA contributes multi-objective optimization for route discovery. This hybridization aims to improve route efficiency, energy utilization, and trust in communication within MANETs.

Conditional Shortest Path Routing and Local Knowledge Metrics:
Hybridizing conditional shortest path routing with local knowledge metrics involves incorporating conditional intermeeting time metrics into traditional routing algorithms. This hybrid approach considers historical node contacts and optimizes paths based on local knowledge. The integration aims to improve routing performance in DTNs by adapting to changing connectivity patterns.

Rule Caching and Flow Forwarding in Software-Defined Networking (SDN):
Combining rule caching and flow forwarding strategies in SDNs introduces a hybrid algorithm for end-to-end delay minimization.

Feedback-Based Probability Selection and AVB Switched Ethernet:
In the context of AVB switched Ethernet, a hybrid approach involves feedback-based probability selection (FBPS) for frame forwarding. FBPS dynamically adjusts the probability of selecting best effort traffic, optimizing queuing delays. This hybridization ensures both high and low priority traffic operate effectively, contributing to improved communication in AVB switched Ethernet.

Collaborative Cache and Network Path Optimization:
The collaborative cache approach, integrated into network path optimization strategies for DTNs, involves a hybrid model. The objective of this hybridization strategy is to reduce the distance between nodes, improve the efficiency of path identification, and optimize cache allocation. This is achieved by employing data-sharing techniques and optimizing paths through the use of collaborative caching.

Energy Efficiency in Bio-Inspired DTN Optimization

When formulating and executing bio-inspired optimization strategies for Delay Tolerant Networks (DTNs), it is imperative to consider the significance of energy efficiency.
This section elucidates the strategies and algorithms employed to enhance energy utilization in Delay Tolerant Networks (DTNs), while scrutinizing the many aspects of energy efficiency within the framework of bio-inspired methodologies.

Energy-Aware Forwarding Strategies:
The focus of research has been on the development of energy-conscious forwarding algorithms for routing protocols in Delay Tolerant Networks (DTNs), as exemplified by the study conducted [7]. These strategies aim to reduce energy use while simultaneously optimizing the transmission of messages. These methods aim to improve the overall energy efficiency of the Delay-Tolerant Network (DTN) by considering the energy levels of nodes and enhancing the forwarding decision-making process based on the availability of energy resources.

Bio-Inspired Energy Efficient Trusted Hybrid Routing Protocol:
In 2019, introduced a hybrid routing protocol for mobile ad hoc networks (MANETs) that is grid-based, bio-inspired, energy-efficient, and trustworthy. This protocol employs bio-inspired optimization techniques to

achieve energy-efficient routing in dynamic mobile networks. The integration of grid-based clusters and multi-objective genetic algorithms contributes to the energy efficiency of communication within the MANET [15].

Challenges and Solutions in Energy Efficiency

While addressing challenges in DTNs, energy efficiency is often a central concern. Challenges may include intermittent connectivity, limited resources, and diverse node capabilities.

Solutions involve adapting bio-inspired optimization methods to dynamically assess and optimize energy consumption based on network conditions. This adaptability contributes to efficient energy utilization in challenging DTN environments.

Optimization of Energy Consumption in Throw Box Deployment

In the optimization of throw box deployment, as presented by [2], energy efficiency is a key focus. Evolutionary algorithms are employed to find optimal locations for throw boxes that maximize coverage while minimizing average delay and maximizing the delivery ratio among nodes. This optimization strategy contributes to energy-efficient communication opportunities in DTNs.

Energy-Aware Routing in Wildlife Tracking Applications

The study by [7] extends the application of energy-aware strategies to wildlife tracking scenarios. In this context, sensors attached to animals transmit data to base stations, and energy-aware forwarding strategies aim to maximize data delivery while efficiently utilizing the limited energy resources on the animal nodes.

Hybrid Approaches for Energy Efficiency

Hybrid approaches, such as combining Particle Swarm Optimization (PSO) with Ant Colony Optimization (ACO) or Genetic Algorithms (GA) with Swarm Intelligence, can be designed to optimize energy efficiency. These hybrid models leverage the strengths of individual algorithms to adapt to changing network conditions and enhance energy-aware decision-making in DTNs.

End-to-End Delay Minimization for Energy Efficiency in SDN:

[9] Proposed an end-to-end delay minimization-based joint rule caching and flow forwarding algorithm for Software-Defined Networking (SDN). While the primary focus is on minimizing delay, the efficient use of resources, including energy, is implicit in achieving optimal system performance.

Network Path Optimization and Collaborative Cache

Network path optimization strategies that utilize collaborative cache, as explored in the work [16], contribute to energy efficiency in DTNs. By optimizing paths based on factors such as cost, transmission speed, and network traffic conditions, these strategies aim to reduce energy consumption while improving overall communication efficiency.

Bio-Inspired Optimization for Energy-Efficient AVB Switched Ethernet

[10] proposed a feedback-based probability selection for frame forwarding in AVB switched Ethernet. This bio-inspired approach ensures that high-priority traffic can enjoy low latency while efficiently managing energy consumption. By dynamically adjusting the probability of selecting best-effort traffic, the algorithm contributes to the overall energy efficiency of AVB switched Ethernet.

DTN Architecture for Challenged Internets:

Fall's (2003) work on a delay-tolerant network architecture for challenged internets addresses scenarios with limited resources. While not explicitly focused on energy efficiency, the architecture's use of wireless sensor networks (WSNs) as relay nodes and packet forwarding networks (PFN) as intermediate nodes indirectly impacts energy consumption in challenged network scenarios [5].

These studies collectively highlight the importance of integrating energy-efficient strategies into bio-inspired optimization techniques for DTNs. As DTNs often operate in resource-constrained environments, optimizing energy consumption is crucial for achieving reliable and sustainable communication. Future research may further explore innovative bio-inspired approaches to enhance energy efficiency in the evolving landscape of DTNs.

Future Directions and Emerging Trends

Emerging developments and interesting future approaches have been made possible by the investigation of bio-inspired optimization for path selection in Delay Tolerant Networks (DTNs). This section highlights new developments that potentially influence the field of bio-inspired DTN optimization and suggests directions for further research [25-33].

Integration of Machine Learning Techniques:
Subsequent investigations may explore the amalgamation of bio-inspired optimization algorithms and machine learning methodologies. Deep learning and reinforcement learning in particular have demonstrated promise in teaching machine learning models to acquire the best possible techniques for difficult decision-making tasks. The adaptability and intelligence of DTN optimization may be improved by combining these models with bio-inspired strategies, especially in dynamic and uncertain contexts.

Dynamic Bio-Inspired Routing Protocols
A promising direction is the creation of dynamic routing protocols inspired by biological systems. These protocols would adjust instantly to variations in node mobility, connectivity patterns, and network conditions. Inspired by natural phenomena like animal swarming, dynamic routing algorithms may provide resilient and adaptable solutions for effective message forwarding in dynamic DTN environments.

Security and Trust in Bio-Inspired DTN Optimization
Future study might concentrate on improving the security and trust aspects of bio-inspired DTN optimization because DTNs frequently function in difficult and hostile contexts. Combining cryptographic methods and trust models with bio-inspired solutions could protect the network from rogue nodes and guarantee message delivery dependability.

Edge Computing and Bio-Inspired Optimization
Emerging Trend: A developing phenomenon, the amalgamation of edge computing and bio-inspired optimization holds the capacity to fundamentally transform the performance of DTNs. Localized processing can be advantageous for bio-inspired algorithms by utilizing periphery computing resources for optimization and decision-making. This can result in decreased latency and improved overall network efficiency.

Autonomous Drone-Based DTNs
The rise of autonomous drones presents an exciting opportunity for bio-inspired DTN optimization. Drones equipped with bio-inspired algorithms could autonomously navigate challenging terrains, establish ad-hoc networks, and optimize message forwarding based on dynamic environmental conditions. This trend aligns with the growing interest in Unmanned Aerial Vehicles (UAVs) for communication and surveillance applications.

Multi-Objective Bio-Inspired Optimization
Extending bio-inspired optimization techniques to address multiple objectives simultaneously is a promising direction. Optimizing for energy efficiency, message delivery ratio, and network lifetime concurrently could lead to more comprehensive solutions. Multi-objective bio-inspired algorithms may provide decision-makers with a range of trade-off options depending on specific DTN requirements.

Standardization and Benchmarking
Standardization efforts and benchmarking practices for bio-inspired DTN optimization algorithms are gaining importance. Establishing common benchmarks, metrics, and evaluation criteria will facilitate fair comparisons between different algorithms and encourage the development of robust and universally applicable solutions.

Cross-Domain Applications
Bio-inspired DTN optimization could find applications beyond traditional scenarios. Exploring cross-domain applications, such as healthcare, disaster management, and smart cities, opens avenues for tailoring bio-inspired algorithms to address specific communication challenges in diverse contexts.

Quantum-Inspired Optimization for DTNs
Emerging Trend: Quantum-inspired optimization algorithms represent an intriguing frontier. Drawing inspiration from quantum mechanics, these algorithms could offer novel ways to solve complex optimization problems in DTNs. Quantum-inspired approaches may unlock new levels of efficiency and scalability for bio-inspired DTN optimization.

Collaborative Research Platforms
Establishing collaborative research platforms and open repositories for bio-inspired DTN optimization algorithms could accelerate progress in the field. Shared datasets, simulation environments, and code repositories would encourage researchers to build upon existing work, fostering a collaborative and cumulative approach to advancing bio-inspired DTN optimization.
The future of bio-inspired optimization for DTNs holds exciting prospects, ranging from the integration of cutting-edge technologies to the exploration of novel applications. Researchers and practitioners alike have the

opportunity to shape the trajectory of this field by addressing emerging challenges and embracing innovative trends. As the demand for reliable and efficient communication in dynamic environments continues to grow, bio-inspired optimization stands poised to play a pivotal role in shaping the future of Delay Tolerant Networks.

Comparison

Theoretical comparison

TABLE I. THEORETICAL COMPARISON [1],[2],[3],[4],[5]

Paper	Author Name	Methods	Performance	Results	Findings	Contributions
"Online Algorithms for Adaptive Optimization"	"Wissam Chahin, Francesco De Pellegrini, Rachid El-Azouzi, Amar Prakash Azad"	Multidimensional stochastic approximation algorithm	Optimal runtime performance	Outperforms existing methods in convergence and stability	This study introduces techniques to optimize data transmission in mobile ad hoc networks, when full information is unavailable and nodes have different mobility characteristics.	Algorithm adapts to network state and node capabilities without requiring full information
"OPTIMIZATION OF THROW BOX DEPLOYMENT"	"S. Sekar, C. Poongodi"	Evolutionary algorithm	Theoretical framework for throw box deployment optimization	Demonstrated effectiveness through comparative simulations	The study offers insightful information about throwbox deployment optimization, which is essential for resolving IoT network intermittent connectivity issues.	Formulation of deployment problem, Maximizes coverage, Minimizes average delay, Maximizes delivery ratio
"Routing in Delay-tolerant network Based on Nodes' Sociality"	"Long Tan, Zixuan Men"	Social network analysis technique	Sociality-based routing to reduce conflicts and increase cooperation among nodes	Theoretical emphasis on improved network performance	Tan and Men's work incorporates sociality-based techniques into DTN routing, which advances the field. Their SAAD protocol is a viable way to deal with connectivity issues in networks that are dynamic and socially driven.	Prioritization of nodes based on social characteristics, Enhanced network performance
"Bio-Inspired Feature Selection"	"Bai Ji, Xiaozheng Lu, Geng Sun, Wei Zhang, Jiahui Li, Yinzhe Xiao"	Binary Particle Swarm Optimization (BPSO)	Modification of BPSO with diversity and inertia features	Superiority over other methods demonstrated in solving diverse optimization challenges	The research provides an effective multi-objective optimization method for choosing the best throwbox deployment locations in a Delay Tolerant Network for the	Exploration of different regions of the search space, Escape from local optima

					Internet of Things (DTN-IoT) environment.	
”A delay-tolerant network architecture”	”Kevin Fall”	Three-layered DTN architecture	Efficiency demonstrated in challenged internets with limited resources	Practical validation through simulation results	An alternative networking model that accepts sporadic connectivity, resource constraints, and asynchronous communication is provided by Kevin Fall's design. This Delay-Tolerant Network Architecture creates new opportunities for communication in difficult settings by breaking from the conventional end-to-end assumptions.	Proposes a novel three-layered DTN architecture using wireless sensor networks, packet forwarding networks, and web services

Performance of various proposed methods

TABLE II: PERFORMANCE OF VARIOUS PROPOSED METHODS [1],[2],[3],[4],[5].

Paper Title	**Methodology**	**Performance Metrics**	**Results**	**Findings**	**Contributions**
”Online Algorithms for Adaptive Optimization”	Multi-dimensional stochastic approximation algorithm	Convergence, Stability	Optimal runtime performance, Outperforms existing methods	Adaptive algorithm for heterogeneous DTNs	Enhanced convergence and stability
”Optimization of Throw Box Deployment”	Evolutionary algorithm for throw box placement	Coverage, Average Delay, Delivery Ratio	Maximizes coverage, Minimizes average delay, Maximizes delivery ratio	Efficient deployment of intermediate relay nodes	Improved resource utilization in DTNs
”Routing in DTN Based on Nodes’ Sociality”	Social network-based routing scheme	Network Cooperation, Conflict Reduction	Improved cooperation, Reduced conflicts	Priority-based routing decisions	Enhanced network cooperation
”Bio-Inspired Feature Selection”	Improved Binary Particle Swarm Optimization (BPSO)	Diversity, Inertia, Feature Selection	Enhanced exploration, Escapes local optima, Improved feature selection	Modified BPSO for feature selection	Superior performance in combinatorial optimization
”DTN Architecture for Challenged Internets”	Three-layer DTN architecture	Bandwidth, Energy, Storage Utilization	Advantages in bandwidth, energy, and storage utilization	Novel architecture for challenged internets	Improved resource efficiency in challenging networks

Comparison of Bio-Inspired Approaches Table [1],[2],[3],[4],[5]

TABLE III. COMPARISON OF BIO-INSPIRED APPROACHES TABLE [1],[2],[3],[4],[5]

Author Name	**Bio-Inspired Algorithm Used**	**Key Features of the Algorithm**	**Application Areas**	**Advantages**	**Disadvantages**
”Wissam Chahin, Francesco De Pellegrini, Rachid El-Azouzi, & Amar Prakash Azad (2013) ”	Stochastic Approximation	Adaptive optimization in Heterogeneous Delay Tolerant Networks (DTNs).	Heterogeneous DTNs (e.g., mobile phones, laptops, sensors)	Real-time adaptability	Dependent on network state and node capabilities without full information
”S. Sekar, & C. Poongodi (2017) ”	Evolutionary Algorithm	Optimization of throw box deployment in DTN.	DTNs with intermediate relay nodes (throw boxes)	Maximizes coverage, minimizes average delay, and maximizes delivery ratio	Requires simulation experiments to demonstrate effectiveness
”Long Tan, & Zixuan Men (2021) ”	Social Network Analysis Technique	Routing based on nodes' sociality in DTN.	DTNs emphasizing cooperation among nodes	Improves network performance by reducing conflicts and increasing cooperation	May require substantial computational resources for sociality analysis
”Bai Ji, Xiaozheng Lu, Geng Sun, Wei Zhang, Jiahui Li, & Yinzhe Xiao (2020) ”	Binary Particle Swarm Optimization (BPSO)	Bio-inspired feature selection for improved optimization using BPSO.	Feature selection in various optimization problems	Incorporates diversity and inertia for enhanced exploration and escaping local optima	Effectiveness may be influenced by the choice of parameters
”Kevin Fall (2003) ”	Not specified	DTN architecture for challenged internets.	Challenged internets with limited resources (bandwidth, energy, storage)	Three-layer architecture (Physical layer with WSNs, Data link layer with PFN, Application layer)	Requires validation through simulation results

Challenges in Delay Tolerant Networks Table [1],[2],[3],[4],[5].

TABLE IV. CHALLENGES IN DELAY TOLERANT NETWORKS TABLE [1],[2],[3],[4],[5].

Author Name	**Challenges Identified**	**Proposed Solutions (if any)**	**Impact on DTN Path Selection**
”Wissam Chahin, Francesco De Pellegrini, Rachid El-Azouzi, & Amar Prakash Azad (2013) ”	Heterogeneity of Nodes	Multi-dimensional stochastic approximation algorithm adapting to nodes' capabilities without full information	Addresses variability in node capabilities, enhancing adaptability
”S. Sekar, & C. Poongodi (2017) ”	Deployment Optimization	Evolutionary algorithm for optimal throw box placement	Optimized deployment enhances coverage, reduces delay, and improves delivery
”Long Tan, & Zixuan Men (2021) ”	Node Sociality-based Routing	Social network analysis to identify social nodes and assign higher routing priority	Improves cooperation among nodes, reducing conflicts in DTN path selection
”Bai Ji, Xiaozheng Lu, Geng Sun, Wei Zhang, Jiahui Li, & Yinzhe Xiao (2020) ”	Feature Selection for Optimization	Improved Binary Particle Swarm Optimization (BPSO) incorporating diversity and inertia	Enhances feature selection in optimization, influencing path selection
”Kevin Fall (2003) ”	Limited Resources in Challenged Internets	Three-layer DTN architecture using wireless sensor networks (WSNs) and packet forwarding networks (PFN)	Supports DTNs in challenged internets with limited resources

Hybrid Approaches in Bio-Inspired Optimization Table [1],[2],[3],[4],[5].

TABLE V. HYBRID APPROACHES IN BIO-INSPIRED OPTIMIZATION TABLE [1],[2],[3],[4],[5].

Author Name	**Hybridization Methods**	**Combination of Algorithms**	**Performance Improvements**
”Wissam Chahin, Francesco De Pellegrini, Rachid El-Azouzi, & Amar Prakash Azad (2013) ”	Stochastic Approximation Algorithm	Multi-dimensional stochastic approximation algorithm	Enhanced convergence and stability
”Bai Ji, Xiaozheng Lu, Geng Sun, Wei Zhang, Jiahui Li, & Yinzhe Xiao (2020) ”	Binary Particle Swarm Optimization (BPSO) + Diversity + Inertia	Improved Binary Particle Swarm Optimization incorporating diversity and inertia	Superior exploration of search space and escape from local optima

III. CONCLUSION AND FUTURE WORKS

The utilization of Bio-Inspired Optimization for path selection in message forwarding has been shown to be highly promising within the realm of Delay Tolerant Networks (DTNs). The integration of algorithms influenced by natural events with the complex obstacles posed by Delay-Tolerant Networks (DTNs) has led to notable progress, specifically in enhancing the dependability of communication in environments characterized by intermittent connectivity and protracted delays. This comprehensive study synthesizes the collective findings derived from a wide range of research efforts, providing a thorough understanding of the current state of Bio-Inspired Optimization in relation to path selection in Delay-Tolerant Networks (DTNs).

The literature review explored various bio-inspired algorithms that offer distinct advantages for transmitting messages in challenging Delay-Tolerant Network (DTN) environments. The adaptability and versatility of bio-inspired approaches are highlighted through theoretical foundations and numerical evaluations, which encompass various aspects such as the real-time adaptability of DTN algorithms, the strategic optimization of relay node deployment using evolutionary algorithms, and the cooperative node routing schemes informed by social network analysis.

Performance Highlights: The examination of performance emphasized the unique contributions of each method, highlighting their efficacy in specific aspects of DTN optimization. The efficacy of adaptive online algorithms was established by their ability to adapt in real-time, while evolutionary algorithms proved their success in strategically positioning relay nodes. Routing systems that are based on sociality, and draw inspiration from social network analysis, have shown promise in reducing disputes and promoting cooperation among nodes. This comprehensive understanding enables professionals to customize their strategies to fulfil specific demands within Delay-Tolerant Networks (DTNs).

As this investigation nears its conclusion, it becomes evident that Bio-Inspired Optimization for Delay-Tolerant Network (DTN) path selection is a vibrant area with significant potential for future advancements. The gaps and obstacles that have been highlighted provide a valuable framework for academics, offering direction towards areas that have yet to be thoroughly investigated. In order to effectively address increasing issues in communication networks, it is imperative that future attempts place a high priority on the enhancement of current algorithms, the investigation of innovative bio-inspired paradigms, and the adaption of these approaches. The future exhibits possibilities for ongoing progress and the realization of the complete capabilities of Bio-Inspired Optimization in facilitating message transmission across Delay Tolerant Networks.

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