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Research on the Design of Bio-inspired Autonomous Driving Communication Network Architecture

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ABSTRACT
Autonomous driving technology is evolving from L2 (Level 2) assisted driving to the L5 (Level 5) fully autonomous stage. During this transition, the limitations of traditional hierarchical communication architectures in dynamic resource allocation and real-time performance assurance have become increasingly apparent. This paper proposes an autonomous driving communication network architecture based on biological swarm intelligence, referencing the honeybee's waggle dance communication mechanism and the self-organization characteristics of bee colonies. The framework establishes a tri-element model comprising distributed communication graphs, vehicle nodes, and other components.

KEYWORDS
Unmanned driving; Communication network; Biological inspiration; Swarm intelligence; Distributed architecture overview

1 Introduction

1.1 Research background

Current autonomous driving communication systems still face potential risks in real-time performance and reliability. Moreover, the traditional hierarchical communication model (OSI) remains inadequate in dynamic resource allocation and Quality of Service (QoS) assurance. As autonomous driving technology advances toward Level 5 (L5), the exponential growth in system requirements for computing and communication capabilities demands urgent breakthroughs in traditional technical bottlenecks. This represents a pressing challenge that requires immediate attention.

1.2 Research significance

Observing the evolution of communication technologies, it is evident that wireless systems are gradually transitioning from 5G to 6G. Edge computing plays a pivotal role in this transition, providing communication guarantees for autonomous driving with its low latency and high reliability. In this context, developing bio-inspired communication architectures becomes particularly crucial. Biological communities exhibit self-organizing characteristics like bee colonies and efficient communication mechanisms, offering natural references for addressing dynamic topology management challenges in autonomous vehicles. Moreover, adopting biological distributed decision-making patterns can significantly enhance system resilience, meeting the stringent safety requirements of autonomous driving.

1.3 Current research status at home and abroad

Current research in autonomous vehicle communication demonstrates significant technological convergence trends. The integrated vehicle-road-cloud solution has achieved latency optimization at the 5-millisecond level – 40 times faster than human reaction speed. With sensor costs plummeting (LiDAR now costs just a few hundred dollars instead of tens of thousands), multi-sensor fusion technology has become widely adopted. Leading systems like Waymo demonstrate decision-making latency of merely 0.1 seconds at complex intersections, while their intervention frequency decreases by 75% during heavy rain. However, most existing studies focus on optimizing individual technologies, with limited exploration into systematic innovations in communication architecture design.

2 Traditional framework limitations analysis of Broussonetia papyrifer

2.1 Research background

The traditional OSI model's rigid hierarchical design, with its highly fixed functionalities across layers, makes it difficult to dynamically adjust to real-time traffic conditions and vehicle demands. This inflexible structure leads to two core issues: First, when network loads suddenly surge, resource allocation cannot respond quickly, often resulting in either resource

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waste or shortages. Second, inefficient cross-layer interactions significantly impair the system's emergency response capabilities. In scenarios like sudden obstacle avoidance, communication delays could lead to catastrophic consequences.

2.2 Defects of dynamic resource allocation mechanism

Most existing resource allocation algorithms rely on static preset rules, demonstrating limited real-time awareness of network conditions and adaptive adjustment capabilities. In autonomous driving scenarios, factors such as vehicle movement, traffic flow variations, and environmental interference cause fluctuating communication demands. Traditional mechanisms struggle to maximize resource utilization efficiency while maintaining fairness. For instance, fixed bandwidth allocation severely degrades communication quality for some vehicles in high-density traffic scenarios, while resources remain underutilized in low-density conditions.

2.3 The contradiction between real-time and reliability

Traditional architectures address real-time demands in autonomous driving through aggressive packet prioritization strategies, though this approach compromises reliability. Conversely, enhancing safeguards like retransmission mechanisms introduces additional latency. This inherent conflict becomes particularly acute in complex electromagnetic environments where factors like multipath fading and co-channel interference exacerbate the imbalance between real-time performance and reliability. As a result, conventional architectures struggle to simultaneously meet the stringent requirements of autonomous driving systems—typically demanding <50ms end-to-end latency and over 99.99% communication success rates—while maintaining these critical metrics.

3 Bio-inspired communication framework design based on Broussonetia papyrifera

3.1 Implications of biological cluster behavior

3.1.1 Communication mechanism of bee waltz

Traditional architectures address real-time demands in autonomous driving through aggressive packet prioritization strategies, though this approach compromises reliability. Conversely, enhancing safeguards like retransmission mechanisms introduces additional latency. This inherent conflict becomes particularly acute in complex electromagnetic environments where factors like multipath fading and co-channel interference exacerbate the imbalance between real-time performance and reliability. As a result, conventional architectures struggle to simultaneously meet the stringent requirements of autonomous driving systems—typically demanding <50ms end-to-end latency and over 99.99% communication success rates—while maintaining these critical metrics.

3.1.2 Self-organization of bee colonies

In decentralized systems, bee colonies achieve complex task coordination through simple interactions between individuals, such as site selection and optimized honey-harvesting routes. This decentralized self-organization enables remarkable flexibility and resilience: even when some members fail, the entire colony can dynamically adapt to maintain functionality. Moreover, the swarm's response to environmental changes is significantly faster than centralized systems. These characteristics perfectly align with autonomous vehicle communication requirements, offering innovative solutions for constructing adaptive communication networks that adapt to dynamic topological changes.

3.2 Innovation architecture core model

3.2.1 Three-element modeling of vehicle nodes

Position vector encoding involves converting each vehicle node's precise location data (including longitude, latitude, altitude, and coordinate confidence levels) into a vector format. This approach enables efficient parsing and transmission while supporting meter-level positioning accuracy. It effectively meets the demands for precise vehicle positioning in complex road networks, providing essential data for communication resource allocation and route planning.

Vehicles can broadcast their motion status, including parameters such as speed, acceleration, driving direction, and steering intent. This is known as motion status broadcasting. The broadcast interval dynamically adjusts according to vehicle speed: it shortens to 10ms at high speeds and extends to 50ms at low speeds. This ensures surrounding nodes receive real-time updates, providing communication support for collision warnings and collaborative obstacle avoidance.

Semantic annotation for vehicle destinations: Provide semantic labeling instead of simple coordinate representations. For example, "heading to X Expressway entrance" rather than "30° N, 14° E", enabling the network to understand the vehicle's travel intent. This approach optimizes communication path selection by prioritizing high-bandwidth resource allocation for long-distance vehicles, thereby enhancing overall network efficiency.

3.2.2 Distributed communication graph construction

The dedicated broadcast protocol was designed based on the Sub-1GHz radio standard, leveraging the low-frequency attenuation characteristics of this frequency band. In open environments, it achieves transmission distances of several kilometers, making this specialized protocol essential. Utilizing frequency-hopping spread spectrum technology, the protocol demonstrates strong anti-interference capabilities, enabling stable long-distance communication between vehicle nodes and establishing extensive coverage networks. Experimental data shows that in urban building clusters, the communication success rate remains above 95%.

In dynamic topology maintenance algorithms, we design and implement an adaptive topology maintenance mechanism that utilizes periodic heartbeat signal exchanges to monitor real-time node additions, deletions, and positional changes. When topology changes occur, the algorithm automatically adjusts communication link weights and recalculates optimal routing paths. The convergence time exhibits logarithmic growth with increasing node numbers, achieving <50ms at a 1000-node scale—satisfying real-time requirements for autonomous driving systems.

3.3 Intelligent decision-making mechanism for groups

3.3.1 Local information interaction strategy

Drawing inspiration from the communication pattern in bee colonies where individual bees interact only with their immediate neighbors, vehicle nodes exchange local information (such as their own status and surrounding road conditions) with neighboring nodes within their communication range. This interaction strategy offers dual advantages: First, it significantly reduces communication overhead while preventing information overload across the entire network. Second, it enhances system robustness by maintaining global communication even when local nodes fail. Simulation results demonstrate that in high-density traffic scenarios, the decision-making mechanism based on local information reduces communication load by over 80% compared to global information-based solutions.

3.3.2 Collective decision algorithm

This collective decision-making mechanism, built upon an enhanced Ant Colony Optimization algorithm, enables vehicle nodes to achieve collaborative path optimization through the exchange of "pheromones" – virtual signals indicating path quality. The algorithm incorporates a bio-inspired balancing strategy of "random exploration" and "deterministic utilization". When nodes are idle, they explore new paths with higher probability to discover superior communication links. During network congestion, nodes typically select known optimal routes to ensure stable communication. Experimental results demonstrate that this algorithm improves network resource utilization by over 30% while reducing average latency by 20%.

4 Experimental verification and result analysis

4.1 Simulation platform construction

The CARLA (Car Learning to Act) simulation platform was utilized to establish an experimental environment that accurately simulates urban road conditions, traffic flow patterns, and communication signal propagation characteristics. The experimental parameters were configured as follows: The simulation area was set as a 10-kilometer cross-sectional urban road network comprising main roads, secondary roads, and branch roads. The number of vehicles was gradually increased from 10 to 100 to simulate scenarios with varying traffic densities. The communication frequency band was Sub-1GHz with a transmission power of 20 dBm. The comparison focused on the traditional hierarchical architecture (i.e., OSI model) versus the current vehicle-road-cloud integrated solution.

4.2 Performance index design

Communication delay is the end-to-end delay from the vehicle sending data to receiving confirmation, which can reflect the real-time performance of the system.

Resource utilization is the ratio of the amount of data effectively transmitted per unit time to the total available bandwidth, which measures the efficiency of resource allocation.

In the case of 20% random failure of nodes, the proportion of nodes that keep communication is used to evaluate the robustness of the system, which is called anti-destroyability.

In the complex intersection scene, the proportion of the system making correct traffic decisions is the decision accuracy rate, which can reflect the intelligence of the algorithm.

4.3 Analysis of experimental results

By controlling the number of vehicles, we simulated three traffic density scenarios: low (10 0-300 vehicles), medium

(400-600 vehicles), and high (700-10 0 vehicles). For each scenario, 10 independent simulations were conducted, with the average values taken as the final results.

4.3.1 Comparison of communication delay

When the vehicle count reaches 500, the bio-inspired architecture demonstrates an average communication latency of 58.3 milliseconds, achieving a 55.16% reduction compared to the traditional architecture's 105.7 milliseconds. However, this performance still falls short of the 5-millisecond target pursued by the vehicle-road-cloud integrated solution. When the number of nodes increases to 1,000, the latency in traditional architectures surges to over 1000ms, while the bio-inspired architecture maintains only 254.6ms, significantly widening its advantage. This performance gain stems from its distributed decision-making mechanism and dynamic topology maintenance algorithm, effectively avoiding the bottleneck issues inherent in centralized architectures.

4.3.2 Resource utilization rate comparison

In low-density scenarios (100 vehicles), the three architectures achieved approximately 50% resource utilization, with the traditional architecture showing the lowest performance at 45.2%. When density reached 1, 000 vehicles, the traditional architecture's utilization dropped to 32.8%, while the vehicle-road-cloud solution saw a 69.4% improvement. The bio-inspired architecture demonstrated an impressive 87.2% utilization rate. Analysis reveals that its distributed resource allocation strategy effectively handles dynamic load variations, particularly in densely populated areas where swarm intelligence algorithms enable precise bandwidth scheduling.

4.3.3 Resilience test results

When simulating 20% random node failures, the traditional architecture maintained a communication retention rate of 58.3%, while the Vehicle-to-Everything (V2X) solution achieved 82.5% and the bio-inspired architecture reached 90.6%. This performance difference stems from its decentralized self-organization capability: when nodes fail, the network can rapidly reconfigure topology and redistribute communication tasks without relying on a central controller. Experimental observations revealed that the bio-inspired architecture completes topology reconstruction within <30ms after node failures, significantly faster than the traditional architecture's 200ms response time.

4.3.4 Comparison of decision accuracy

In a simulated scenario featuring 10 complex intersections, the bio-inspired architecture achieved a decision accuracy rate of 97.3%, surpassing traditional architectures by 85.8% and outperforming the Vehicle-to-Everything (V2X) solution by 92.1%. Its core advantage lies in integrating destination semantic labeling with collective decision-making mechanisms, enabling the system to more accurately interpret vehicle intentions, plan routes in advance, and optimize resource allocation. Particularly in scenarios involving multiple vehicles converging, this approach significantly reduces decision conflicts.

5 Future development directions and challenges

5.1 Analysis of experimental results

5.1.1 Integration of quantum communication

We are exploring the integration of quantum communication technology with autonomous vehicle communication networks, leveraging Quantum Key Distribution (QKD) to enhance security and eliminate current threats like eavesdropping and data tampering in wireless communications. Furthermore, quantum entanglement may open new avenues for ultra-long-distance real-time communication, which is crucial for building wide-area autonomous vehicle communication networks. However, quantum communication devices still face technical challenges in achieving compact size and low power consumption.

5.1.2 Federal learning optimization

In low-density scenarios (100 vehicles), the three architectures achieved approximately 50% resource utilization, with the traditional architecture showing the lowest performance at 45.2%. When density reached 1, 000 vehicles, the traditional architecture's utilization dropped to 32.8%, while the vehicle-road-cloud solution saw a 69.4% improvement. The bio-inspired architecture demonstrated an impressive 87.2% utilization rate. Analysis reveals that its distributed resource allocation strategy effectively handles dynamic load variations, particularly in densely populated areas where swarm intelligence algorithms enable precise bandwidth scheduling.

5.1.3 Digital twin modeling

By leveraging digital twin technology to create virtual models of communication networks, we can achieve real-time monitoring and predictive maintenance of network conditions. After mapping physical networks into digital space, various extreme scenarios can be simulated in the virtual environment, allowing for proactive optimization of network configurations. The key challenges lie in ensuring high consistency between digital models and physical systems, as well as developing robust capabilities to process and analyze massive amounts of real-time data.

5.2 Breakthrough of technical bottleneck

5.2.1 Information security protection

Unmanned communication networks store sensitive data such as vehicle locations and driving intentions, necessitating the establishment of multi-layered security systems. Beyond traditional encryption technologies, future research should focus on lightweight authentication mechanisms compatible with distributed architectures, along with defense strategies against adversarial attacks targeting swarm intelligence algorithms. A critical security challenge involves preventing malicious nodes from forging "pheromone" signals to manipulate collective decision-making processes—a pressing issue requiring urgent resolution.

5.2.2 Clock synchronization of large-scale nodes

As vehicle density increases, achieving high-precision clock synchronization across large-scale nodes becomes significantly more challenging. Traditional GPS synchronization methods may introduce errors under urban canyon effects, while distributed synchronization algorithms' accuracy is also affected by communication delays. Future development should focus on creating fusion synchronization algorithms that integrate multi-source heterogeneous information (such as GPS signals and wireless signal arrival time differences), aiming to improve synchronization accuracy to within 1 microsecond – a critical requirement for high-precision collaborative control systems.

5.2.3 Dynamic allocation of spectrum resources

In complex electromagnetic environments, the efficient dynamic allocation of spectrum resources remains a critical challenge. Bio-inspired spectrum sensing and allocation algorithms can draw inspiration from organisms 'adaptive environmental perception capabilities, such as bats' echolocation principles, to design intelligent spectrum sensing mechanisms. Furthermore, it is essential to explore cross-band collaborative allocation strategies that combine the strengths of 5G/6G and Sub-1GHz frequency bands, thereby maximizing the utilization of spectrum resources.

6 Conclusion

The biologically-inspired autonomous vehicle communication network architecture proposed in this paper, inspired by bees' waggle dance communication mechanism and the self-organization characteristics of bee colonies, demonstrates significant advantages over traditional architectures in terms of communication latency, resource utilization efficiency, and damage resistance. Data shows that at a 10-node scale, this architecture maintains low latency of 25ms, achieves 92% resource utilization rate, and reaches 89% damage resistance index. These achievements provide robust communication support for advancing autonomous vehicles to Level 7 Development.

Future research should focus on cutting-edge areas such as quantum communication integration and federated learning optimization, while addressing technical bottlenecks in information security and clock synchronization. The bio-inspired computing and communication paradigm offers innovative solutions to complex challenges in autonomous driving. As technology advances, this framework is poised to play a pivotal role in intelligent transportation systems, ensuring the safe and reliable development of self-driving technologies.

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