

Applications of Self-Organising Systems

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Introduction

Self-Organization

- Swarm Intelligence
- Decrease of Entropy
- Autopoiesis
- Artificial Systems

Emergence

- Decentralized control and local interactions
- Local information and direct/indirect interactions

Methodology



**Research objectives and
questions**

Selection Criteria

Search Strategy

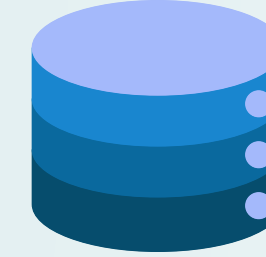
Quality Assessment

Data Extraction

Research Objectives and Questions

- What are the key characteristics and principles that define Self-Organising Systems across various domains?
- How are Self-Organising Systems practically implemented in different fields, such as sensor networks, traffic management, and distributed software systems?
- What methodologies and models are commonly used to harness the selforganizing properties of SOS?
- How do different SOS implementations address issues of scalability, resilience, and emergent behavior?

Search Strategy

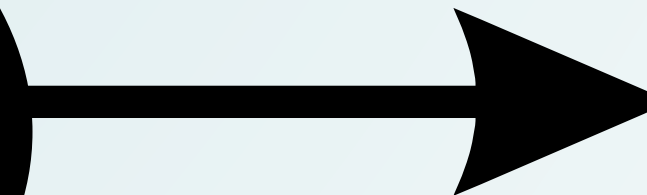


Searched Databases

Google Scholar
IEEE Xplore
Springer Link
ACM Digital Library

Initial Search Keywords

Self-Organising Systems
Applications of self-organising
systems
Real world self-organising
systems
Emergence and self-organising



Elicit



Data extraction from case studies

- 1 - Self-Organising Communities in Distributed Information Systems Using Middle Agents**
- 2 - Self-Organization as a Supporting Paradigm for Military UAV Relay Networks**
- 3 - Self-organized Routing for Road Networks**

Self-Organising Communities in Distributed Information Systems Using Middle Agents



Develop a distributed information system that leverages self-organizing principles and autonomous middle agents to flexibly and effectively organize users and resources

User Agents

Each user has an associated User Agent that registers with at least one Middle Agent to access system services.

Middle Agents

These manage user interactions and service matching, acting as matchmakers, facilitators, or brokers, depending on privacy concerns.

Schemes of middle-agents



Search Scheme

Checking local databases
Consulting neighbor middle-agents
Keyword based methods



Award Scheme

Evaluate outcomes
Positive and negative marks
Promotion of users



Exchange Scheme

Communication with
responsible middle agent
Facilitate exchange
Foster community formation

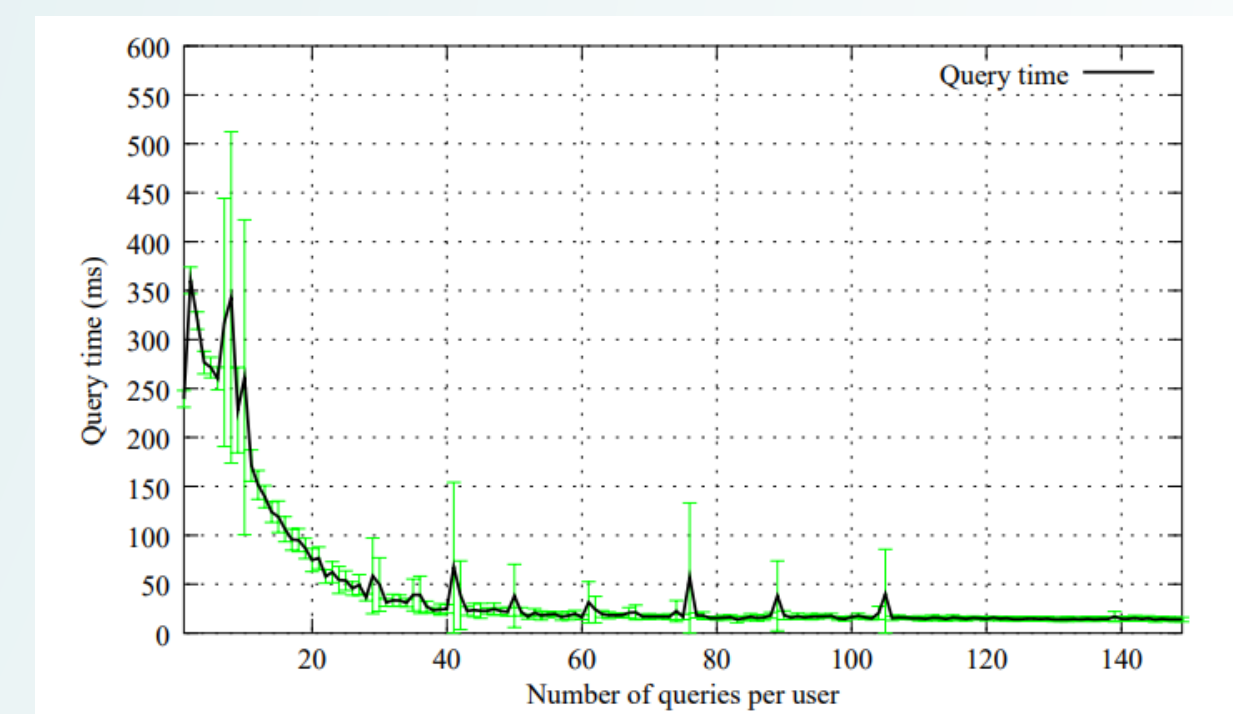
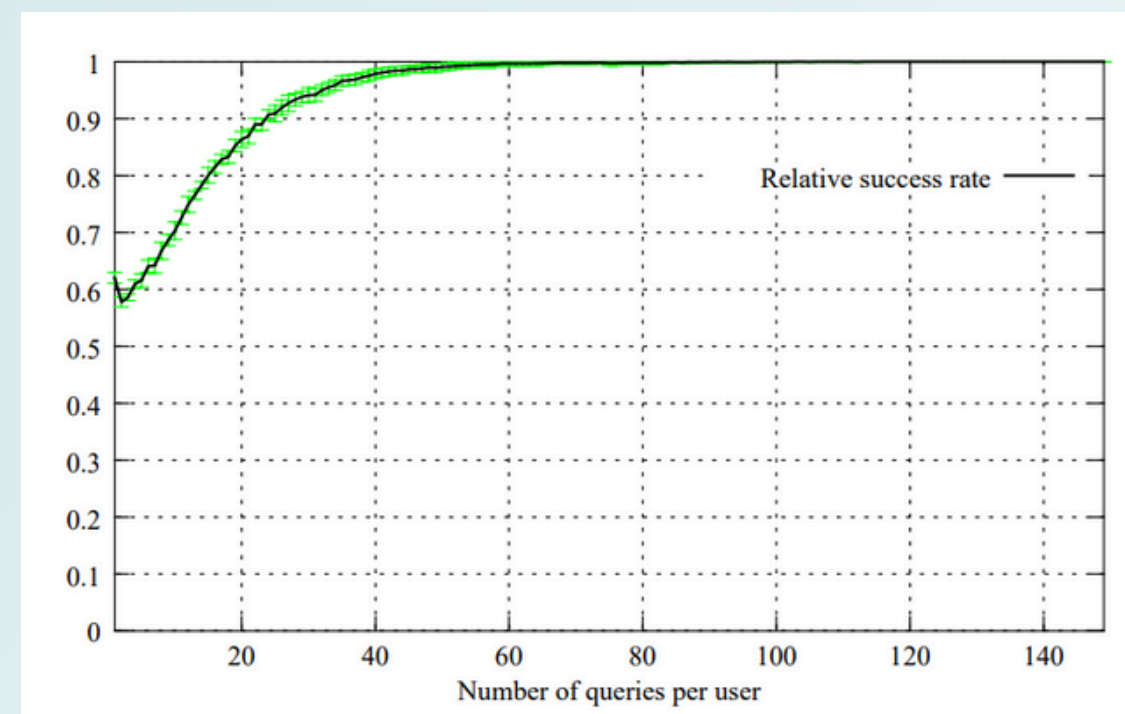
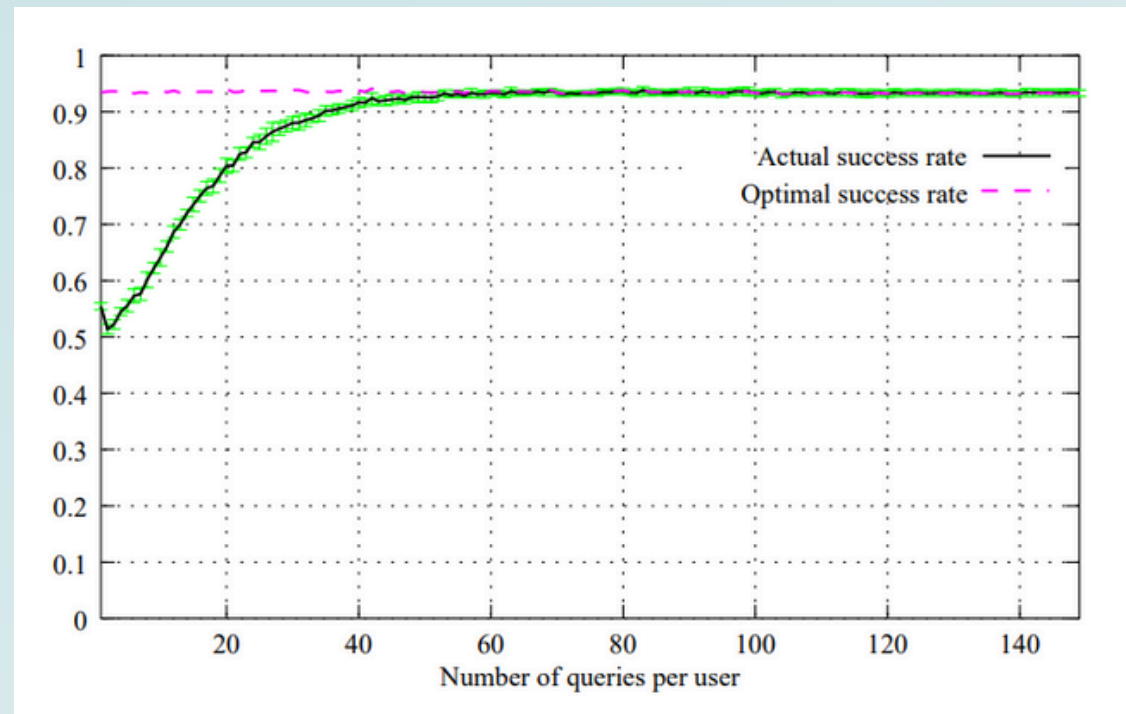
Experiments

The experiment involved documents categorized into ten topics: Business, Education, Entertainment, Health, Law, Literature, Politics, Science and Technology, Sport, and Travel. Each user focused on one category and sought to obtain documents in that category that they did not already own. The primary task for users was to find documents in their category that they did not possess.

Initially, users randomly registered with one of the fifteen middle agents. The queries in the experimental setup were titles of documents, and answers were names of identified providers if there were any. If there was not a suitable response for the query in the local database, a middle agent could try a maximum of five other middle agents in the system, which were selected randomly.

In the experiments, users continuously generated queries over a set period, with the query frequency centered around a mean value, Q . Each user had a specific interest in one document category and owned random documents within that category. Users collectively possessed about 95% of the documents in any given category, ensuring a broad distribution of documents and the likelihood that some queries would fail.

Outcomes



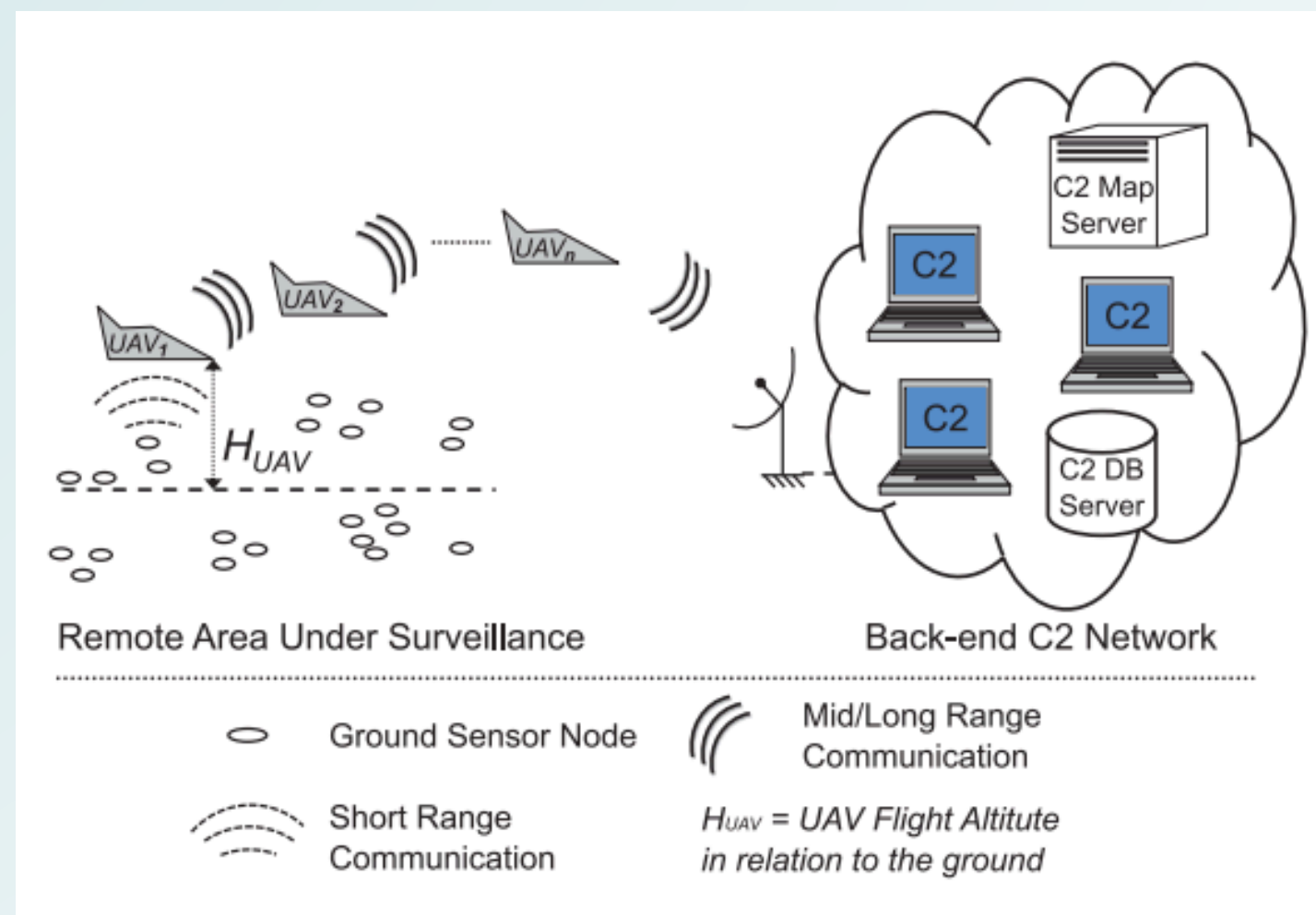
As can be seen from figures above, which show the improved search results and accelerated search time within a system of 2000 users, the system's ability to find correct answers to queries enhanced over time as more queries were initiated, leading to better search results.

Figures show that user communities were established after each user submitted approximately 56 queries. Once these communities formed, the actual success rate nearly matched the optimal rate, and the relative success rate reached close to 1. At the same time, the average search time for a query significantly dropped from 375 milliseconds to a much lower value. Although there was some fluctuation in search time due to communication and processing delays after community formation, it eventually stabilized around 14 milliseconds.

Self-Organization as a Supporting Paradigm for Military UAV Relay Networks

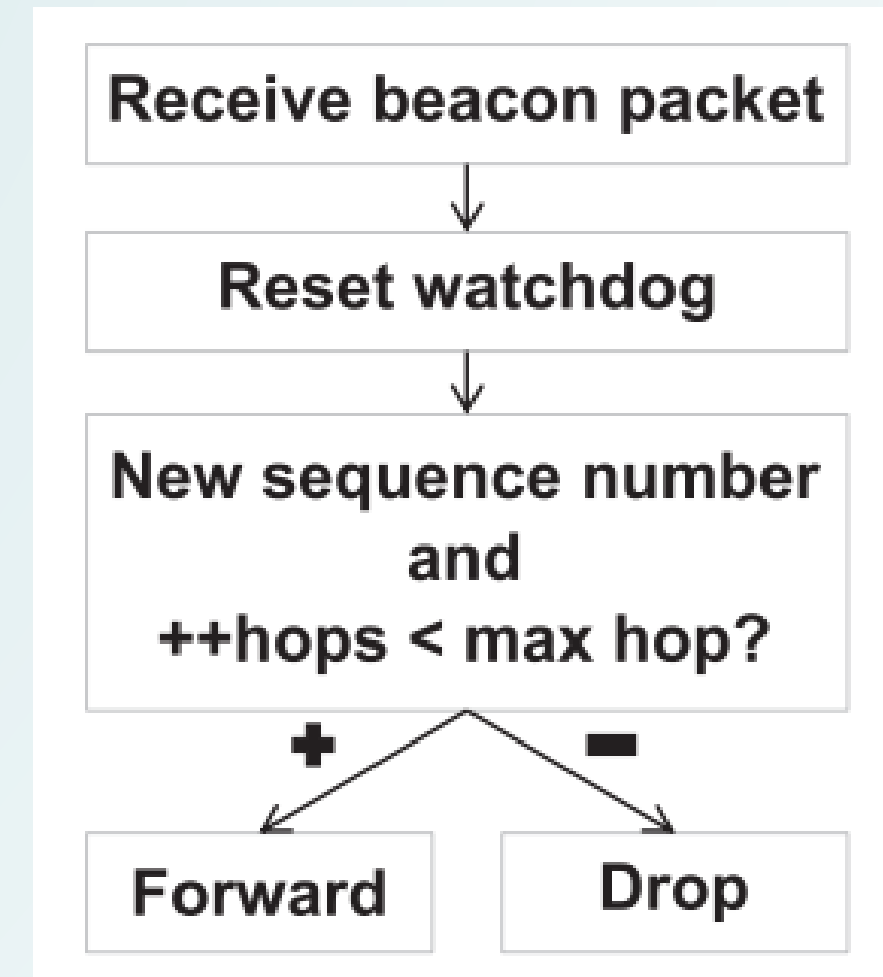
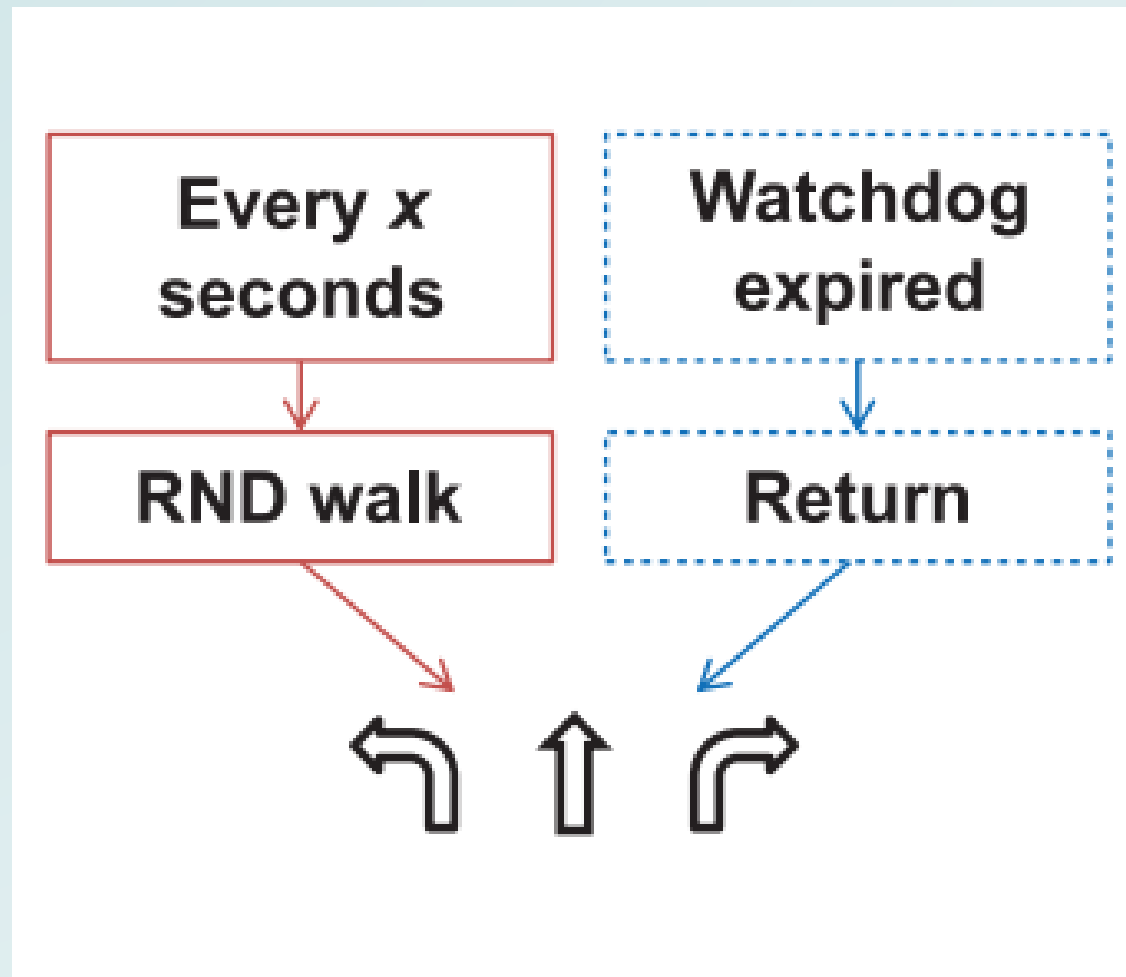


Enhancing the deployment of autonomous UAV teams in military operations by leveraging self-organizing principles to improve cooperative mission performance, including target tracking, surveillance, patrolling, and relay network formation, ensuring effective communication and connectivity for tactical edge devices and networks.



Design

In a multi-goal UAV mission, reconnaissance and maintaining a relay network are competing objectives. Reconnaissance benefits from UAVs spreading out to maximize area coverage (positive feedback), while maintaining the relay network requires UAVs to stay closer to preserve connectivity (negative feedback).

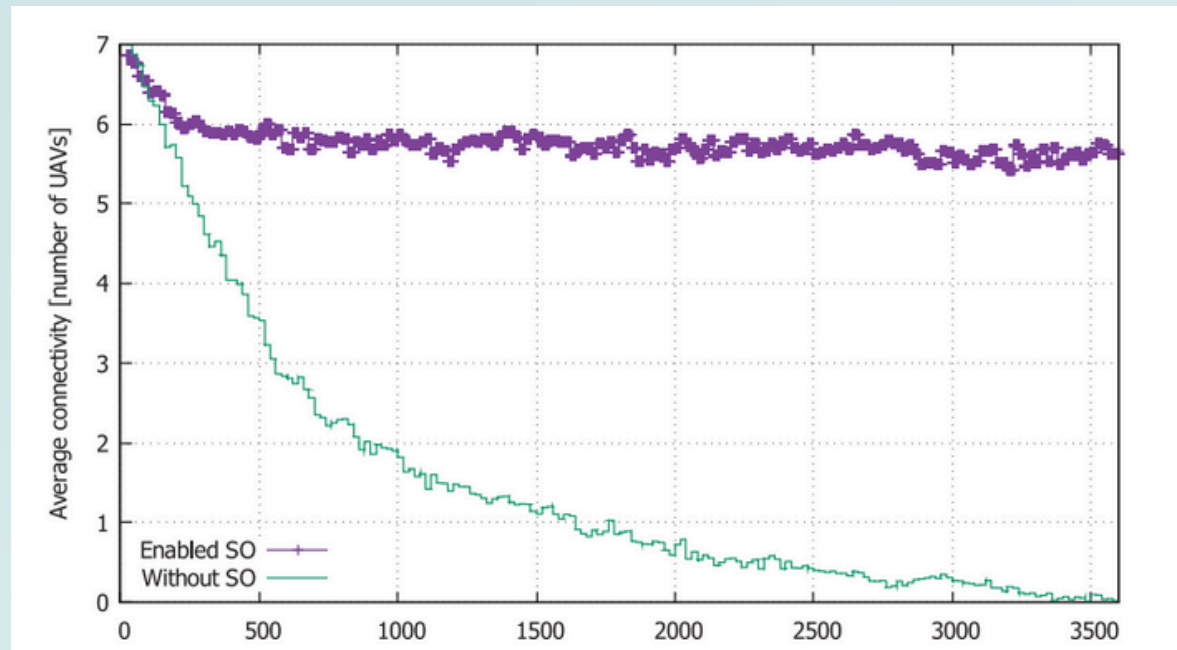


Experiments

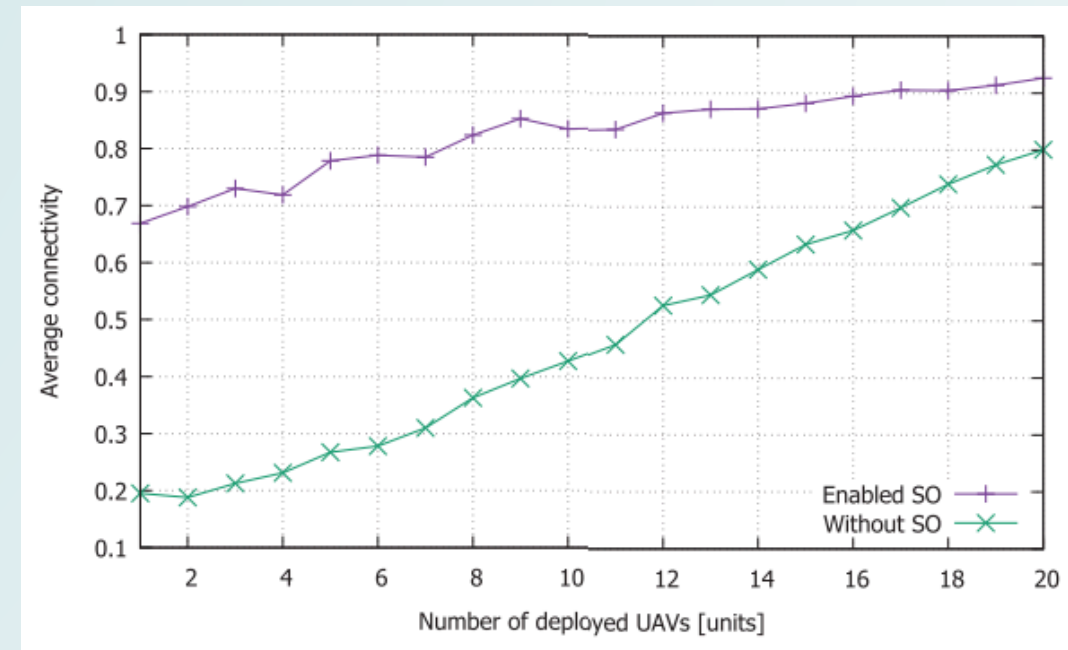
Experiments used a modified Simbeeotic simulator with communication models based on IEEE wireless standards. While the SO algorithm is protocol-independent, IEEE 802.15.4 was employed for UAV communication, providing over 300 meters of range and supporting connectivity to isolated WSNs. UAVs avoided collisions with a 45-degree right turn, and key parameters are detailed in table below.

TABLE I SIMULATION PARAMETERS	
Parameter	Value
mission duration	3600 seconds
surveillance area	square of 10x10 km
maximal speed	100 km/h
flying altitude	250 m
802.15.4 tx power	25 dBm
rx SNR margin	10 dBm
rx sensitivity	-10 dBm
propagation model	free space optical
mobility model	random walk

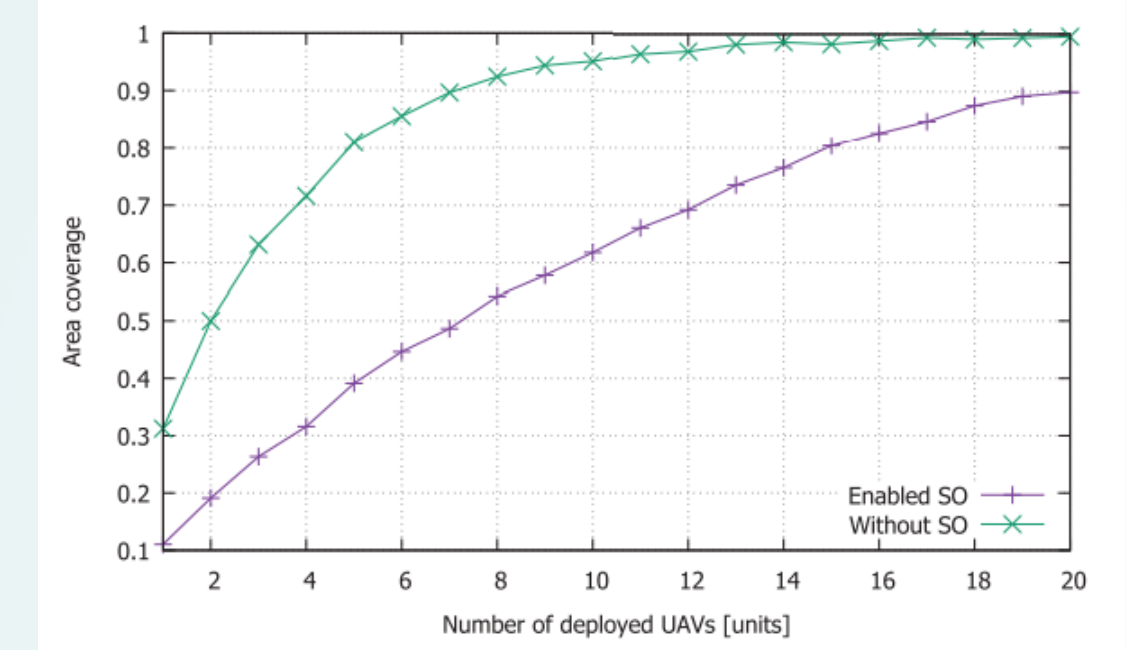
Outcomes



Average connectivity to the base station over a one-hour mission with seven UAVs shows steady decline without the self-organizing solution (green line), while the solution stabilizes connectivity at 5.8 (violet line). Results are based on 50 simulation runs, with initial high connectivity due to UAV launch positions.



Average connectivity of the relay network, where 1.0 indicates full connectivity, is compared between the self-organizing relay algorithm and random walk, based on 50 simulation runs for varying numbers of deployed UAVs.



Area coverage (1.0 means full coverage) when the proposed selforganizing algorithm is enabled or disabled (pure random walk) as a function of the number of deployed UAVs. Average values of 50 simulation runs per point are shown

Self-Organized Routing for Road Networks



Rapid urbanization and increased mobility have intensified traffic challenges globally. To address this, Organic Traffic Control (OTC), a self-organizing, adaptive system inspired by Organic Computing principles, is proposed as a solution. This study extends OTC with a dynamic route guidance system modeled after Internet routing protocols to improve resilience against congestion and blockages, validated through simulations under various traffic conditions.

Self-Organized Route Guidance

- Routing component (RC)
- Route updates based on real-time traffic data
- Delay estimates from the observer/controller components

Distance Vector Routing for Road Networks

- Identifying key destinations
- Routing table entry creation; destination, turn, travel time
- Distance-based travel time, average delay from red lights

Link State Routing for Road Networks

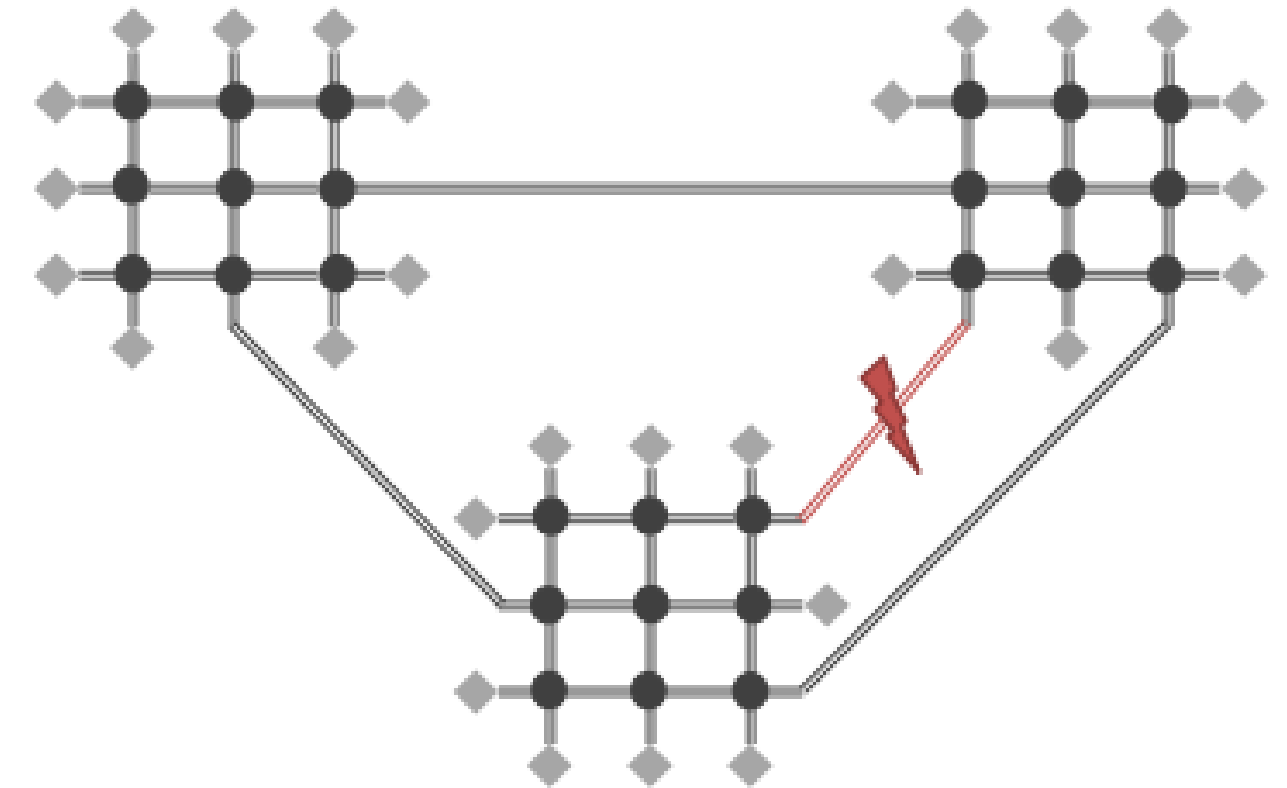
- Broadcasts estimated travel times for turning movements
- Calculation of link states for each path connecting previous intersection to next
- Network graph creation by combining the link states

Experiments

The evaluation has been conducted for a simulated network that consists of three subnetworks, illustrated in figure on the right side. The network includes 27 signalized intersections (circles) and 28 prominent destinations (diamonds). Each subnetwork is connected by single-lane road segments, 250 meters long, with two turning lanes starting 100 meters before intersections. The regions are linked by two-lane roads.

Two scenarios were tested:

- **Regular scenario:** 8 vehicles per hour travel from each origin to each destination, totaling 6,048 vehicles per hour. This uncongested scenario, simulated over 3 hours, assesses DRG's impact under normal conditions.
- **Incident scenario:** The same traffic volume is simulated, but one road between sub-networks is blocked for 20 minutes, starting 15 minutes into the 2-hour simulation. This scenario evaluates DRG's effectiveness during disturbances.

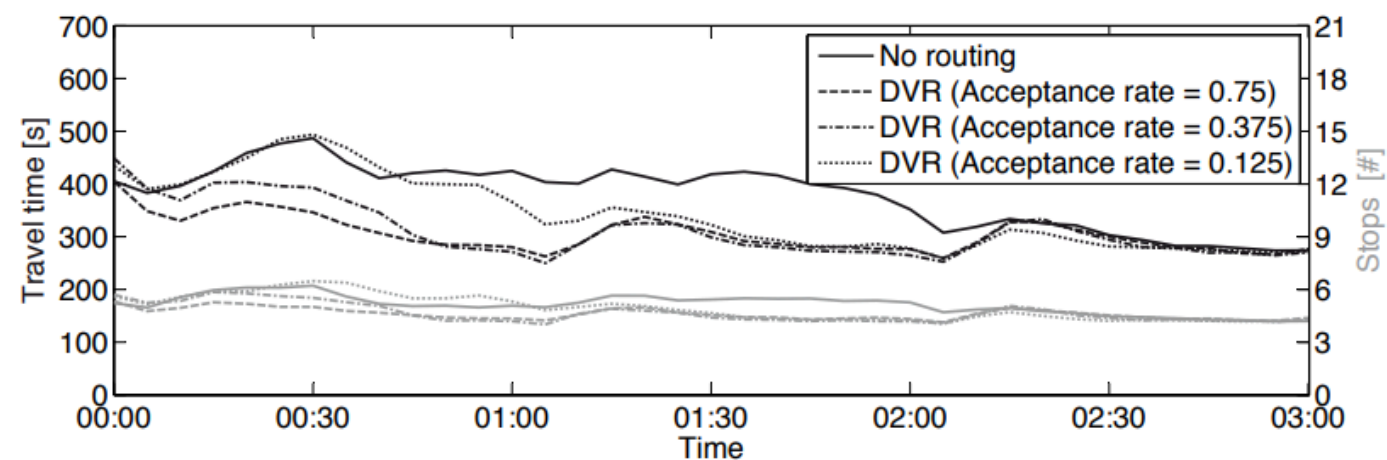


Driver acceptance rates of 0.125 (low), 0.375 (medium), and 0.75 (high) have been used for both scenarios. The routing protocols were run every 150 seconds and evaluated based on the average travel time and number of stops per vehicle. Additionally, total fuel consumption and pollution emissions were analyzed to assess the environmental impact of the DRG system

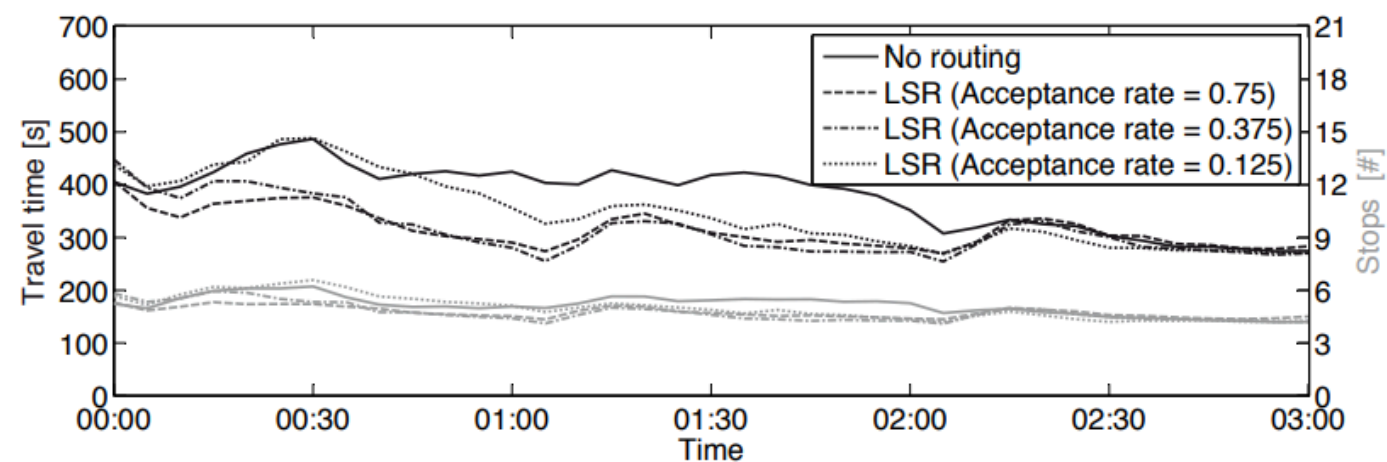
Outcomes for regular scenario

The results show that DRG benefits regular traffic conditions. Regardless of the acceptance rate, both routing protocols reduce average travel times and stops, leading to lower fuel consumption and emissions in most cases

	Ref.	Distance Vector Routing			Link State Routing		
		0.125	0.375	0.75	0.125	0.375	0.75
Travel time [s]	378	342 (9.5 %)	312 (17.5 %)	305 (19.3 %)	348 (7.9 %)	315 (16.7 %)	316 (16.3 %)
Stops [#]	5.14	4.92 (4.3 %)	4.66 (9.3 %)	4.61 (10.3 %)	5.00 (2.7 %)	4.73 (8.0 %)	4.75 (7.6 %)
Fuel [l]	187.6	190.5 (−1.5 %)	182.4 (2.8 %)	178.9 (4.6 %)	192.5 (−2.6 %)	185.0 (1.4 %)	184.9 (1.4 %)
CO [kg]	811.3	784.4 (3.3 %)	721.9 (11.0 %)	707.2 (12.8 %)	797.0 (1.8 %)	731.4 (9.8 %)	731.8 (9.8 %)
HC [kg]	63.9	61.5 (3.8 %)	56.2 (12.1 %)	55.0 (13.9 %)	62.4 (2.3 %)	56.8 (11.1 %)	56.8 (11.1 %)
NO _x [kg]	13.8	13.2 (4.3 %)	12.0 (13.0 %)	11.7 (15.2 %)	13.4 (2.9 %)	12.2 (11.6 %)	12.1 (12.3 %)



(a) Distance Vector Routing



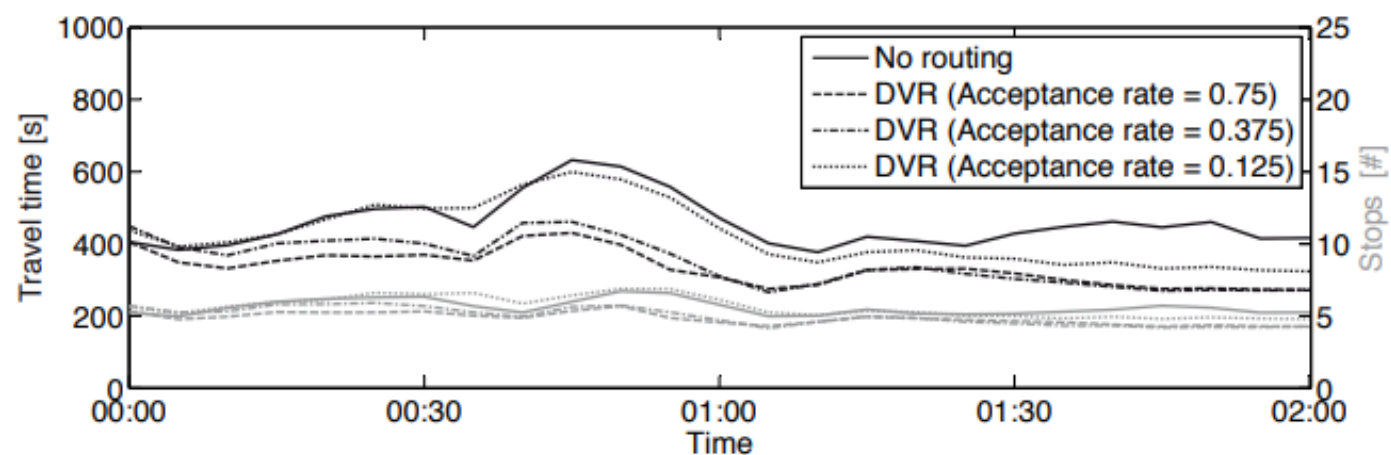
(b) Link State Routing

Figure on the left side illustrates the average travel times and stops during the simulation. DVR and LSR reduce both metrics, particularly in the first two hours, when the observer/controller components are still learning and traffic signals are not yet fully optimized, leading to queues on some roads. This creates opportunities for DRG to be effective. Once the signal plans are near-optimal at all intersections, queues are minimal, reducing the overall benefit of routing, though it remains noticeable.

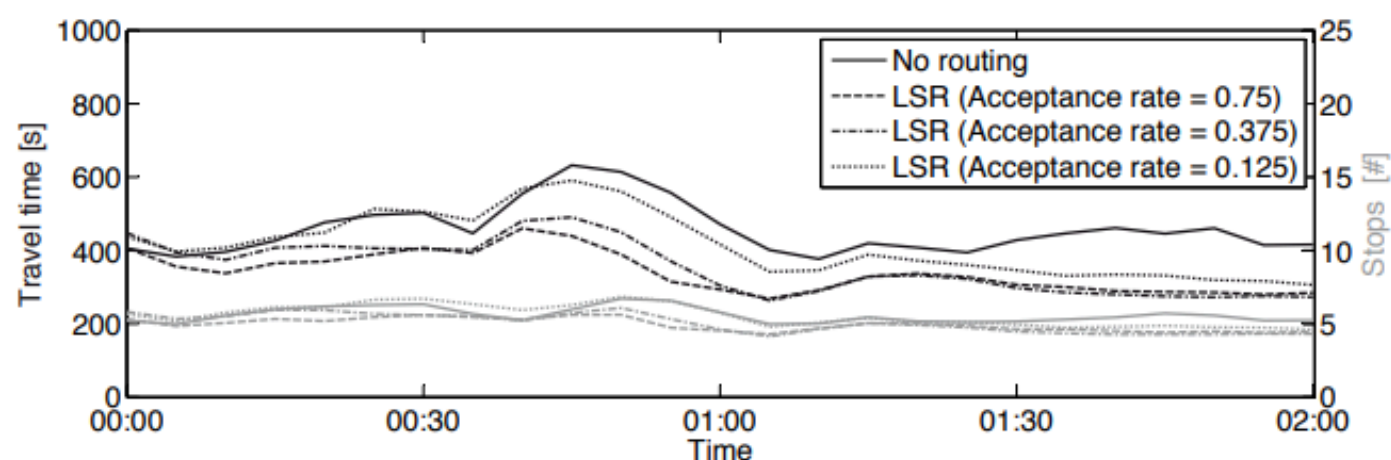
Outcomes for incident scenario

Implementing the DRG mechanism improves average travel time and reduces the number of stops for drivers. The only exception is a slight increase in stops for DVR at a low acceptance rate. System performance improves across all response variables as the acceptance rate increases.

	Ref.	Distance Vector Routing			Link State Routing		
		0.125	0.375	0.75	0.125	0.375	0.75
Travel time [s]	457	422 (7.7 %)	349 (23.6 %)	333 (27.1 %)	414 (9.4 %)	354 (22.5 %)	340 (25.6 %)
Stops [#]	5.60	5.62 (-0.4 %)	4.97 (11.3 %)	4.83 (13.8 %)	5.56 (0.7 %)	5.05 (9.8 %)	4.94 (11.8 %)
Fuel [l]	204.8	213.7 (-4.3 %)	194.3 (5.1 %)	187.8 (8.3 %)	212.4 (-3.7 %)	197.4 (3.6 %)	193.1 (5.7 %)
CO [kg]	636.4	632.3 (0.6 %)	528.9 (16.9 %)	507.9 (20.2 %)	622.5 (2.2 %)	538.0 (15.5 %)	521.0 (18.1 %)
HC [kg]	51.3	50.4 (1.4 %)	41.8 (18.5 %)	39.9 (22.2 %)	49.6 (3.3 %)	42.4 (17.3 %)	40.9 (20.3 %)
NO _x [kg]	10.9	10.8 (0.9 %)	8.8 (19.3 %)	8.4 (22.9 %)	10.6 (2.8 %)	9.0 (17.9 %)	8.6 (18.9 %)



(a) Distance Vector Routing



(b) Link State Routing

Figure on the left side shows the mean travel time and number of stops over the course of the simulated period. The peak observed around after 35 minutes, lasting through the first simulated hour, indicates that the incident impacts both response variables. When no route recommendations are available, uninformed drivers attempt to use blocked routes, leading to increased travel times and stops. DRG helps mitigate these negative effects, regardless of the routing protocol used. Additionally, both travel times and stops quickly return to normal levels after an incident, demonstrating that DRG enhances the road network's robustness against disruptions such as road work or accidents

Conclusion

- Analyzed self-organization in three domains:
 - Distributed Information Systems
 - Military UAV Relay Networks
 - Road Traffic Networks
- Key Insights:
 - **Distributed Information Systems:** Self-organizing middle agents optimize information flow without central coordination.
 - **Military UAV Relay Networks:** Improved communication resilience and adaptability in dynamic environments.
 - **Road Traffic Networks:** Organic traffic control enhances traffic flow, reduces congestion, and adapts to real-time conditions.
- Simulation results:
 - Simulations confirm the effectiveness of self-organizing systems in complex, dynamic scenarios.
- Future directions:
 - Further testing in real-world scenarios is needed to unlock full potential.
 - Findings provide a strong foundation for advancing distributed problem-solving approaches.