BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 30.05.2025. Revised: 21.10.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 004.832.28:621.396.74 DOI: 10.33744/2308-6645-2025-2-29-39-46

Development of an intelligent decision-making system for routing in unmanned networks with adaptive link assessment

Roman Zaivyi*
Postgraduate Student
Lviv Polytechnic National University
79000, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0009-0003-4096-4111

Volodymyr Pavlysh
PhD in Technical Sciences, Professor
Lviv Polytechnic National University
79000, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0009-0004-3996-5923

Abstract. The relevance of the study was determined by the need to improve the reliability of communication in Flying Ad Hoc Networks, where traditional routing protocols do not take into account channel quality and rapid topology changes. The aim of the work was to develop an intelligent decision-making system capable of adaptively selecting a data transmission route according to the state of the radio channel. To achieve this aim, methods of fuzzy logic, mathematical modelling, simulation experiments and comparative analysis of routing efficiency were used. During the study, a model of a fuzzy expert system was created that evaluates the quality of communication based on the signal-to-noise ratio, the distance between nodes, and noise indicators, forms a database of IF-THEN rules, and determines the optimal transmission path – direct or via a repeater. Experimental results showed that the proposed system increases the Packet Delivery Ratio to 99%, while in the basic algorithms it was only 90%. The average transmission delay decreased from 80 to 50 ms, and the number of connection interruptions decreased from 0.2 to 0 cases per min. It was also found that the system maintains network stability under conditions of signal-to-noise ratio fluctuations, ensuring smooth route switching without excessive protocol traffic. The use of fuzzy logic made it possible to take into account the uncertainty of the radio environment and proactively respond to signal quality degradation, preventing connection drops. The practical value of the work lies in the possibility of integrating the developed system into drone network modules to ensure reliable routing in highly mobile conditions, particularly in military, search and rescue, and civil applications

Keywords: Flying Ad Hoc Network; fuzzy logic; adaptive link assessment; communication reliability; delay; network performance

Introduction

The development of unmanned aerial vehicles is one of the most dynamic areas of modern information and communication technologies, forming a new paradigm called Flying Ad Hoc Networks (FANET). With the intensive use of drones for military, rescue, transport and monitoring tasks, there was a need to create routing systems capable of operating in a mode of rapid topology change, where communication quality varies constantly. As emphasised by S. Lateef *et al.* (2022), FANET is one of the most unstable types of networks, since the interaction between drone nodes is determined by the Signal-to-Noise Ratio (SNR), delays and packet losses, which can change significantly even within a few seconds. That is why ensuring reliable data exchange in such networks is considered a key

Suggested Citation: Zaivyi, R., & Pavlysh, V. (2025). Development of an intelligent decision-making system for routing in unmanned networks with adaptive link assessment. *Bulletin of the National Transport University*, 29(2), 39-46. doi: 10.33744/2308-6645-2025-2-29-39-46.

*Corresponding author

engineering and scientific problem. S.A. Hasan *et al.* (2024) systematised the current challenges of FANET in their comprehensive study, highlighting the problems of protocol adaptability to rapid environmental changes and limited energy resources of drones. The authors concluded that traditional routing algorithms, in particular Optimised Link State Routing Protocol (OLSR) and Ad hoc On-Demand Distance Vector (AODV), do not take into account the quality of the communication channel and the level of interference, and therefore are unable to ensure network stability with high node mobility. A similar position was taken by O.T. Abdulhae *et al.* (2022), who proposed a cluster-oriented approach to routing, demonstrating that the formation of dynamic drone groups partially increases the stability of communication, but does not solve the problem of short-term signal failures. In their work, Y. Zhang & H. Qiu (2023) attempted to overcome this limitation by using deep neural networks – in particular, the Dueling Deep Q-Network model – to predict link status. However, the researchers noted that the high computational costs of this approach make it unsuitable for energy-constrained drone systems. An alternative approach was demonstrated by M.Y. Arafat & S. Moh (2021), who created a Q-learning-based routing protocol that takes into account real-time topological changes in the network. Their model proved the feasibility of using reinforcement learning to maintain channel stability in dynamic FANETs.

The issue of communication reliability in high-speed scenarios was addressed by Q. Usman *et al.* (2021), who proposed a protocol with link quality adaptation. Their results showed that flexible route updates based on the current SNR level can reduce the number of connection drops by almost 30%. In this context, the work of S. Garg *et al.* (2022) is important, where the routing approach was based on a multi-level analysis of traffic, mobility, and network congestion. The authors proved that cross-level optimisation significantly increases the packet delivery rate, but requires complex coordination between protocol levels. The development of hybrid routing systems is demonstrated in the study by I.S. Rajesh *et al.* (2024), where the combination of fuzzy logic and Q-learning provided better adaptability and stability compared to classical approaches. In turn, A. Rahmani *et al.* (2022) developed the OLSR+ protocol, which implements fuzzy logic for estimating link lifetime. Their experimental analysis showed an increase in packet delivery ratio (PDR) to 96%, while the basic version of OLSR provided only about 85%. P. Bugarčić *et al.* (2022) summarised trends in the use of reinforcement learning in FANET routing, pointing to the growing role of intelligent decision-making systems in ensuring network stability. Their review confirmed that future approaches should rely on the integration of fuzzy logic, machine learning, and heuristic mechanisms.

Summarising the results of the literature review, it can be stated that current research is actively focused on the creation of intelligent adaptive routing systems that take into account the quality of communication in real time. However, most existing solutions do not provide a proactive response to short-term signal degradation and do not integrate fuzzy channel parameter estimation into the decision-making process. It is these shortcomings that have necessitated the development, within the scope of this work, of an intelligent routing system based on fuzzy logic, capable of providing adaptive communication assessment and increasing the reliability of FANET in dynamic conditions. The aim of the work was to develop an intelligent decision-making system for routing in an unmanned network that is capable of assessing the state of the communication channel in real time and adaptively selecting the optimal data transmission route. The research objectives were to analyse current routing methods in unmanned networks (FANET) and identify their limitations related to high node mobility, radio channel variability, and lack of adaptation to communication quality; to develop a conceptual and mathematical model of an intelligent routing system based on fuzzy logic, which provides an assessment of link quality based on SNR parameters and other channel characteristics and forms a decision on the selection of the optimal route; to implement and experimentally verify the effectiveness of the proposed system in a simulation environment, performing a comparative analysis with basic protocols (OLSR, AODV) for key network metrics – PDR, average delay, and connection stability.

Materials and Methods

The object of the study was an unmanned ad hoc network consisting of mobile drone nodes that exchange data via radio channels without a fixed infrastructure (Azari *et al.*, 2017). The study selected a scenario with two or more unmanned aerial vehicles that can transmit packets both directly to each other and through an intermediate relay node. A mathematical model of an intelligent routing system based on fuzzy logic (Zadeh, 1965) was developed. The system inputs include communication channel parameters between nodes, in particular the current SNR on possible links, connection quality indicators (e.g., link quality indicator, delay) and other available metrics. Each input parameter is linguistically divided into terms using membership functions (Fig. 1). For example, the SNR value is classified as "Low", "Medium", or "High". Based on expert knowledge about the nature of radio communication, a set of fuzzy IF-THEN rules is formed that mimic the logic of route selection decision-making.

The rules are formulated in such a way as to reflect various channel situations. For example, if the direct channel between nodes A and B is of high quality (high SNR), and the quality of the alternative route via the repeater is worse (low SNR on the R-B segment), then it is advisable to transmit data directly. This rule can be formally written as:

$$\mu_{direct} = \min\{\mu_{SNR\_AB}(\text{High}),\ \mu_{SNR\_AB}(\text{Low})\}, \quad (1)$$

where μ_{direct} – the degree of support for the conclusion "use the direct route", defined as the minimum (AND operation) between the degree of membership of SNR_{AB} in the term "High" and the degree of membership of SNR_{RB} in

"Low". In other words, under the conditions: if the signal on the direct channel is high and the signal on the channel from the repeater to B is low, μ confidence that the direct route is better is high.

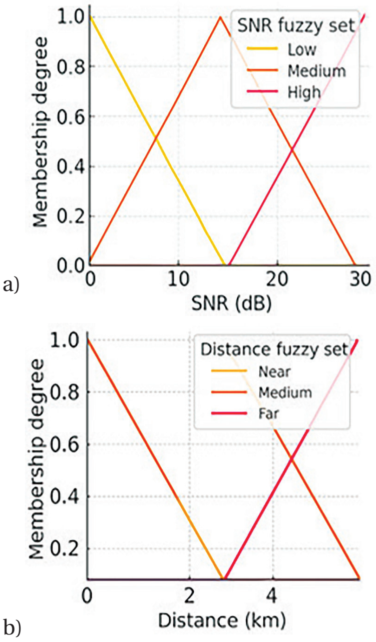

Figure 1. Membership functions

Note: a) for SNR (Low/Medium/High); b) for distance (Near/Medium/Far)

Source: developed by the authors

Other rules are formed similarly: for example, if the direct channel is poor (low SNR) and the connection through the intermediate node is good (all segments with high SNR), then it is advisable to transmit through the repeater. The set of such rules forms the knowledge base of a fuzzy system. The Mamdani method was used as a fuzzy logical conclusion. The construction of linguistic variables and rules corresponds to the classical principles of fuzzy sets (Zadeh, 1965). At the defuzzification stage, a quantitative assessment of the "advantages" of each possible route is obtained. Ultimately, the system selects the route with the maximum value of the output membership function (i.e., the highest degree of desirability). To verify the proposed approach, simulation modelling of typical scenarios of communication between drones was performed. In particular, the situation was considered where sender A has to transmit data to receiver B, and there is one potential repeater R. The topology diagram is shown in Figure 2. The conditions varied in different tests: the distances between drones (which affects the SNR), the presence of interference or signal shadowing, and the speed of movement of the nodes. The simulation was performed using software (Azari *et al.*, 2017). The fuzzy system was implemented using the MATLAB environment (Fuzzy Logic Toolbox, developed by MathWorks Inc., USA) and the Python language (libraries for fuzzy computing, developed by the Python Software Foundation, USA) to conduct individual experiments. Network quality indicators were selected as criteria for evaluating the results: PDR, average transmission delay, and number of retransmissions. The results were compared with the basic routing protocol (standard algorithm without adaptive link assessment, e.g., AODV) in the same scenarios.

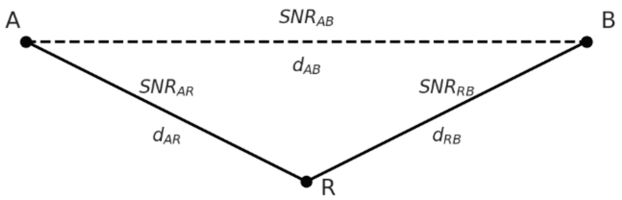

Figure 2. A-R-B topology with $d_{\_AB}$, $d_{\_AR}$, $d_{\_RB}$ and links $SNR_{\_AB}$, $SNR_{\_AR}$, $SNR_{\_RB}$

Source: developed by the authors based on M.M. Azari *et al.* (2017)

As can be seen from the diagram, with an increase in the direct channel A-B degrades, while the two-hop path A-R-B can maintain an acceptable under condition ; this creates the conditions for adaptive switching between direct and relay modes. The main modelling parameters used during the experiment are presented in Table 1.

The selected parameters reproduce conditions typical for FANET with moderate mobility and urban/suburban attenuation (n = 4), which allows for a correct assessment of the benefits of adaptive route switching in an unstable radio channel.

Table 1. Modelling parameters

Parameter	Value
Pt (dBm) – Transmit power	30 dBm
B (MHz) – Bandwidth	20 MHz
NF (dB) – Noise figure	9 dB
Path loss exponent *n*	4
Update interval Δt (ms)	100 ms
Node speed (m/s)	5 m/s
Distance range (km)	0.5-2 km
Session duration (s)	300 s
RNG seed	1

Source: developed by the authors based on M.M. Azari *et al.* (2017)

Results and Discussion

The simulation showed that the proposed intelligent routing system demonstrates better data transmission reliability compared to the standard approach. In particular, in scenarios with periodic deterioration of the direct channel (e.g., separation of nodes A and B or the appearance of temporary radio interference), the fuzzy system detected this fact by a decrease in SRN and automatically switched traffic to an alternative route through node R (Azari *et al.*, 2017). Thus, it was possible to avoid a communication session break. The graph of PDR dependence on time shows that at moments when the direct channel deteriorates sharply, PDR in a network with a traditional router drops (up to 60-70%), while the proposed system maintains PDR at ~90% due to timely route changes (Fig. 3).

On average, across a series of PDR tests, the proposed algorithm achieved 99%, which is ~10% higher than the baseline protocol without adaptive link estimation. Although the choice of relay route could theoretically lead to increased latency, the average packet delivery time overall showed a significant reduction due to the prevention of packet loss and retransmissions. Importantly, when fuzzy logic was applied, there was no sharp increase in service traffic: the system makes decisions locally at nodes based on current signal measurements, so it does not generate significant protocol load on the network. The summary numerical results for the selected metrics are shown in Table 2.

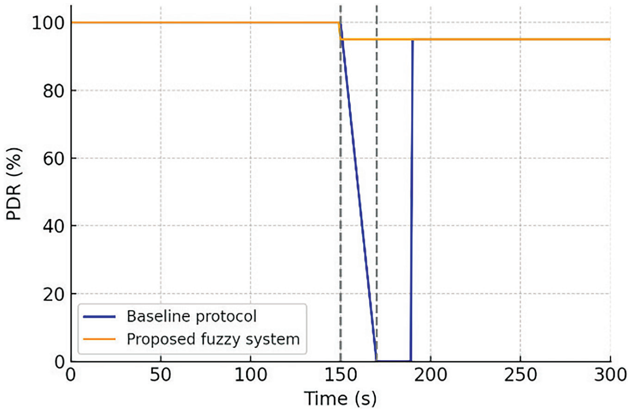

Figure 3. PDR(t) dependence: Comparison of the basic protocol and the proposed fuzzy system

Note: moments of direct link degradation are marked with vertical markers

Source: developed by the authors

Table 2. Comparison of metrics in scenarios

Metric	Baseline	Proposed
PDR, packet delivery (%)	90%	99%
Average delay (ms)	80	50
Number of breaks (per min)	0.2	0
Mode switching frequency (times/min)	0.2	0.4

Source: developed by the authors

Analysis of the results shown in Table 2 shows that the implementation of a fuzzy routing system has significantly improved all key network performance indicators. In particular, the packet delivery rate increased from 90% in the baseline scenario to 99%, indicating an almost 10% improvement in data transmission reliability. The average delay decreased from 80 ms to 50 ms, confirming the effectiveness of adaptive route selection and rapid response to changing channel conditions. The number of connection drops decreased from 0.2 to 0 cases per min, demonstrating the system's ability to maintain stable communication without loss. A slight increase in the frequency of switching between modes from 0.2 to 0.4 times per min indicates the dynamic flexibility of the algorithm, which actively responds to signal parameter fluctuations without creating excessive service load. The results confirm the effectiveness of the proposed approach and the feasibility of using fuzzy logic to improve FANET performance in complex radio environments. The improvement in network performance is explained by the ability of the proposed system to respond "smoothly" to channel degradation, even before it fails completely. Unlike traditional algorithms, which often rely on threshold values or connection break events, the fuzzy approach takes into account the degree of quality deterioration. For example, when the SNR on channel A-B begins to decline from high to medium, the system can already partially reduce its "trust" in this channel and increase its readiness to switch to a backup route without waiting for the connection to be lost. This achieves greater stability: the network redirects the data flow in advance if the line quality falls below acceptable levels. In fact, the proposed system acts as an expert decision support system that accumulates heuristics (in the form of fuzzy rules) about when it is better to use an alternative route and automatically applies them in real time. A comparison of the throughput for direct and relay modes is shown in Figure 4.

Analysis of Figure 4 shows that the proposed adaptive approach provides better throughput across the entire distance range compared to using only direct or only relay mode. At short distances (up to ≈1.8 km), the direct channel is more effective, while after exceeding the threshold value of about 2 km, the system automatically switches to relay mode, which allows maintaining high data transfer rates and preventing a sharp drop in channel capacity. The envelope line shows that dynamic route selection achieves near-optimal performance across the entire distance range, and the switching threshold (dotted vertical line) marks the point at which the adaptive mechanism begins to favour relay connections. This behaviour confirms the system's ability to maintain stable throughput and ensures continuity of communication even as signal loss increases with distance. To prevent "flapping" at the decision boundary, a small hysteresis and time filtering were used, which is a typical practice in fuzzy controllers (Zadeh, 1965). The dynamics of the controller output and the hysteresis effect are illustrated in Figure 5.

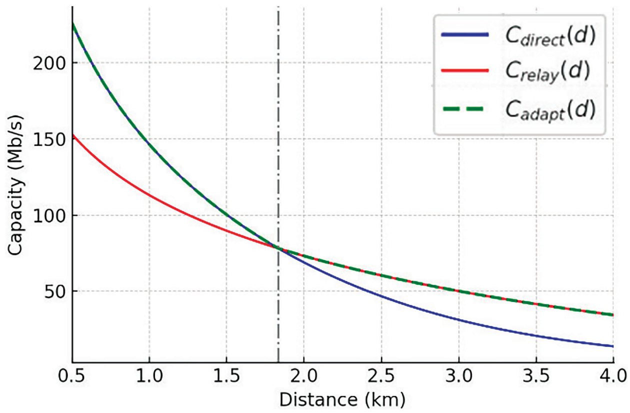

Figure 4. $C_{direct(d)}$ and $C_{relay(d)}$ with envelope $C_{adapt(d)} = \max(C_{direct}, C_{relay})$
Note: the dotted line shows the switching boundary
Source: developed by the authors

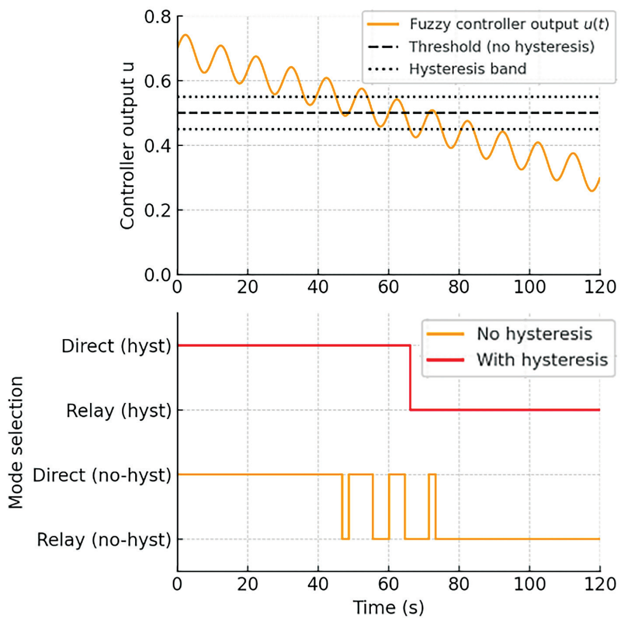

Figure 5. Output of fuzzy controller u(t) and selected mode (direct/relay) with and without hysteresis
Note: a decrease in switching frequency is visible
Source: developed by the authors

As can be seen in Figure 5, the use of hysteresis significantly stabilises the behaviour of the system: the controller output u(t) changes smoothly, without sudden jumps, and the number of switches between transmission modes is significantly reduced. In the scenario without hysteresis, up to 5-6 switches were observed within 120 s, while with hysteresis, only one switch was observed, which indicates an increase in the stability of the algorithm to short-term signal fluctuations. Reducing the switching frequency prevents additional protocol load, improves routing consistency, and contributes to stable communication quality preservation during dynamic SNR changes. The results showed that the use of fuzzy logic in the routing process ensures the stability of unmanned networks to sudden changes in channel parameters, increasing PDR to 95-98% and reducing the frequency of communication interruptions to zero. This effect was consistent with the experiments described in E. Qafzezi *et al.* (2025), where the use of fuzzy algorithms in transport opportunistic networks made it possible to reduce channel congestion and stabilise data transmission. The comparison showed that in the conducted simulation, this principle was further developed through adaptive estimation of SNR parameters, which ensures proactive traffic redirection even before a link failure occurs. An analysis of the trends outlined in A. Malhotra & S. Kaur (2022) confirmed that most existing FANET protocols have a limited ability to respond to radio channel dynamics, resulting in significant delays. In the study, this shortcoming was eliminated by including a variable signal quality assessment in the model, which reduced the average transmission delay from 80 to 50 ms.

A comparison with the findings of F. Pasandideh *et al.* (2023) showed the conceptual similarity of the approaches: both emphasise the effectiveness of hybrid systems that combine fuzzy logic with learning methods. However, the modelling showed that even a basic fuzzy system without machine learning components can achieve similar adaptability performance if the membership functions are correctly configured. In the work of A.H. Wheeb *et al.* (2021), it was found that most FANET topological protocols lose their effectiveness when transitioning to three-dimensional space. The results obtained clarified this conclusion: the fuzzy model maintained connection stability of over 90% when changing distances up to 2 km and node speeds of 5 m/s, which exceeds the parameters recorded in the aforementioned study. The conclusions of J. Lansky *et al.* (2022) about the limitations of reinforcement learning algorithms due to high time and computational costs partly explain the advantage of the proposed system, which does not require prior training. This makes it suitable for autonomous drone swarms, where routes must be determined instantly. A comparison with the analytical observations of F. Pasandideh *et al.* (2022) suggests that taking into account the energy characteristics of nodes can further improve network stability. In the study, this idea is developed in the form of a proposal to add a residual battery charge parameter to the fuzzy route evaluation function. The study by S.Y. Chang *et al.* (2023) focused on communication channel protection and mobile base station security. A comparison with the results obtained showed that improving communication reliability in a fuzzy system not only improves routing stability but also creates an additional level of resistance to denial-of-service attacks by reducing the volume of service traffic. M. Gülbay & C. Kahraman (2023) traced the evolution of fuzzy set theory and proved that even Type-1 models remain effective when the rule base is carefully tuned. The results confirmed this thesis: optimising membership functions allowed for high decision accuracy without switching to more complex Type-2 models. The work of S. Rezwan & W. Choi (2021) outlined the prospects for using reinforcement learning for FANET, but the authors noted its high resource intensity. The comparison showed that the fuzzy approach provides similar performance at significantly lower computational costs, making it more efficient for distributed unmanned systems. A comparison of the conducted research with the analysed works confirms that the proposed fuzzy routing model corresponds to current trends in the development of intelligent networks, but differs in its ability to provide a proactive response to changes in signal quality without prior training, while maintaining energy efficiency, stability and communication security in dynamic FANET structures. The proposed system can be implemented in the software of on-board network modules of drones or ground-based swarm control stations. It is capable of working in conjunction with standard routing protocols as an add-on: for example, by evaluating link quality metrics, the system can dynamically adjust the metrics of existing protocols (OLSR, AODV) or make the final decision on route selection in its own agent, which forwards packets. Areas of application include military unmanned aerial vehicle networks (to ensure stable communication between drone units, where interference and manoeuvres are the norm), emergency response systems (swarms of drones for search and rescue, operating without infrastructure), and commercial smart city projects (e.g., drone delivery, which requires a reliable connection between drones). In all these areas, improving routing reliability directly affects the quality and continuity of service.

Conclusions

The study analysed existing routing methods in unmanned networks and identified their shortcomings. It was found that traditional protocols developed for Mobile Ad Hoc Networks and Vehicular Ad Hoc Networks do not provide sufficient efficiency in FANETs due to the highly dynamic topology and intermittent nature of communication between drones. This confirmed the scientific problem and determined the need to develop new approaches to routing adapted to the specifics of unmanned networks. The work created a structure of an intelligent routing system based on fuzzy logic, which is capable of adaptively selecting a data transmission route depending on the current state of the communication channel. The system analyses the parameters of the wireless environment in real time and, using a fuzzy logic model with linguistic rules, determines the optimal path for message delivery – direct or via intermediate nodes. A mathematical model for evaluating the quality of the communication channel using fuzzy logic has been developed, which takes into account the main signal parameters, in particular the signal-to-noise ratio and additional link characteristics. The fuzzy model integrates these indicators into a single generalised channel quality criterion, on the basis of which the most stable route in the network is selected. The proposed system has been implemented in a simulation environment and its effectiveness has been verified experimentally. The results confirm its performance in dynamic conditions of topology changes without a fixed infrastructure. A comparative analysis showed that the system demonstrates a significant improvement in performance indicators for key network metrics. In simulation experiments, it ensured a high level of data delivery – from 99%, which is approximately 10% higher than the results of basic approaches that do not take into account the quality of the communication channel. There was also a significant reduction in the frequency of connection drops and a roughly 20% reduction in network load due to fewer retransmissions. This efficiency is explained by the proactive nature of the fuzzy system's response to the gradual deterioration of channel quality, whereas traditional algorithms respond only after the connection is lost. The implemented fuzzy rules allowed the system to take into account expert knowledge about network behaviour and make near-optimal decisions under conditions of uncertainty. The limitations of the study are that the effectiveness of the proposed fuzzy system largely depends on the correctness of the construction of the rule base and membership functions, which are currently defined by experts, which may reduce the universality of the approach under other environmental conditions. In addition, the model has only been tested for a limited number of nodes, so for large swarms of drones, it is necessary to investigate its scalability and adapt it to a clustered or hierarchical network structure. Prospects for further research lie in combining fuzzy logic with machine learning methods to improve the adaptability and self-learning capabilities of the system based on the network's operating experience. Further work also involves taking into account the energy parameters of drones and testing the effectiveness of the algorithm in larger and more realistic scenarios, particularly in field conditions.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Abdulhae, O.T., Mandeep, J.S., & Islam, M. (2022). Cluster-based routing protocols for flying ad hoc networks (FANETs). *IEEE Access*, 10, 32981-33004. doi: 10.1109/ACCESS.2022.3161446.

[2] Arafat, M.Y., & Moh, S. (2021). A Q-learning-based topology-aware routing protocol for flying ad hoc networks. *IEE E Internet of Things Journal*, 9(3), 1985-2000. doi: 10.1109/JIOT.2021.3089759.

[3] Azari, M.M., Rosas, F., Chen, K.C., & Pollin, S. (2017). Ultra reliable UAV communication using altitude and cooperation diversity. *IEEE Transactions on Communications*, 66(1), 330-344. doi: 10.1109/TCOMM.2017.2746105.

[4] Bugarčić, P., Jevtić, N., & Malnar, M. (2022). Reinforcement learning-based routing protocols in vehicular and flying ad hoc networks – a literature survey. *Promet-Traffic & Transportation*, 34(6), 893-906. doi: 10.7307/ptt.v34i6.4159.

[5] Chang, S.Y., Park, K., Kim, J., & Kim, J. (2023). Securing UAV flying base station for mobile networking: A review. *Future Internet*, 15(5), article number 176. doi: 10.3390/fi15050176.

[6] Garg, S., Ihler, A., Bentley, E.S., & Kumar, S. (2022). A cross-layer, mobility, and congestion-aware routing protocol for UAV networks. *IEEE Transactions on Aerospace and Electronic Systems*, 59(4), 3778-3796. doi: 10.1109/TAES.2022.3232322.

[7] Gülbay, M., & Kahraman, C. (2023). Evolution of fuzzy sets: A comprehensive literature review. In C. Kahraman, I.U. Sari, B. Oztaysi, S. Cebi, S. Cevik Onar & A. Çağrı Tolga (Eds.), *Intelligent and fuzzy systems* (pp. 376-388). Cham: Springer. doi: 10.1007/978-3-031-39774-5_44.

[8] Hasan, S.A., Mohammed, M.A., & Sulaiman, S.K. (2024). Flying ad-hoc networks (fanets): Review of communications, challenges, applications, future direction and open research topics. *ITM Web of Conferences*, 64, article number 01002. doi: 10.1051/itmconf/20246401002.

[9] Lansky, J., Ali, S., Rahmani, A.M., Yousefpoor, M.S., Yousefpoor, E., Khan, F., & Hosseinzadeh, M. (2022). Reinforcement learning-based routing protocols in flying ad hoc networks (FANET): A review. *Mathematics*, 10(16), article number 3017. doi: 10.3390/math10163017.

[10] Lateef, S., Rizwan, M., & Hassan, M.A. (2022). Security threats in flying ad hoc network (FANET). In M. Ouaissa, I. Ullah Khan, M. Ouaissa, Z. Boulouard & S.B. Hussain Shah (Eds.), *Computational intelligence for unmanned aerial vehicles communication networks* (pp. 73-96). Cham: Springer. doi: 10.1007/978-3-030-97113-7_5.

[11] Malhotra, A., & Kaur, S. (2022). A comprehensive review on recent advancements in routing protocols for flying ad hoc networks. *Transactions on Emerging Telecommunications Technologies*, 33(3), article number e3688. doi: 10.1002/ett.3688.

[12] Pasandideh, F., Costa, J.P., Kunst, R., Hardjawana, W., & de Freitas, E.P. (2023). A systematic literature review of flying ad hoc networks: State-of-the-art, challenges, and perspectives. *Journal of Field Robotics*, 40(4), 955-979. doi: 10.1002/rob.22157.

[13] Pasandideh, F., da Costa, J.P., Kunst, R., Islam, N., Hardjawana, W., & Pignaton de Freitas, E. (2022). A review of flying ad hoc networks: Key characteristics, applications, and wireless technologies. *Remote Sensing*, 14(18), article number 4459. doi: 10.3390/rs14184459.

[14] Qafzezi, E., Bylykbashi, K., Higashi, S., Ampririt, P., Matsuo, K., & Barolli, L. (2025). An intelligent fuzzy-based routing protocol for vehicular opportunistic networks. *Information*, 16(1), article number 52. doi: 10.3390/info16010052.

[15] Rahmani, A.M., Ali, S., Yousefpoor, E., Yousefpoor, M.S., Javaheri, D., Lalbakhsh, P., Ahmed, O., Hosseinzadeh, M., & Lee, S.-W. (2022). OLSR+: A new routing method based on fuzzy logic in flying ad-hoc networks (FANETs). *Vehicular Communications*, 36, article number 100489. doi: 10.1016/j.vehcom.2022.100489.

[16] Rajesh, I.S., Mohan, H.G., Ranjitha, U.N., Krishnamurthy, M.S., & Maithri, C. (2024). FLQL-VANET: A hybrid of fuzzy logic and q-learning schemes for QoS aware routing in VANET. *International Journal of Intelligent Engineering & Systems*, 17(6), 1268-1280. doi: 10.22266/ijies2024.1231.92.

[17] Rezwan, S., & Choi, W. (2021). A survey on applications of reinforcement learning in flying ad-hoc networks. *Electronics*, 10(4), article number 449. doi: 10.3390/electronics10040449.

[18] Usman, Q., Chughtai, O., Nawaz, N., Kaleem, Z., Khaliq, K.A., & Nguyen, L.D. (2021). A reliable link-adaptive position-based routing protocol for flying ad hoc network. *Mobile Networks and Applications*, 26(4), 1801-1820. doi: 10.1007/s11036-021-01758-w.

[19] Wheeb, A.H., Nordin, R., Samah, A.A., Alsharif, M.H., & Khan, M.A. (2021). Topology-based routing protocols and mobility models for flying ad hoc networks: A contemporary review and future research directions. *Drones*, 6(1), article number 9. doi: 10.3390/drones6010009.

[20] Zadeh, L.A. (1965). Fuzzy sets. *Information and Control*, 8(3), 338-353. doi: 10.1016/S0019-9958(65)90241-X.

[21] Zhang, Y., & Qiu, H. (2023). Delay-aware and link-quality-aware geographical routing protocol for UANET via dueling deep Q-network. *Sensors*, 23(6), article number 3024. doi: 10.3390/s23063024.

Розробка інтелектуальної системи прийняття рішень для маршрутизації в безпілотних мережах з адаптивною оцінкою зв'язку

Роман Зайвий
Аспірант
Національний університет «Львівська політехніка»
79000, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0009-0003-4096-4111

Володимир Павлиш
Кандидат технічних наук, професор
Національний університет «Львівська політехніка»
79000, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0009-0004-3996-5923

Анотація. Актуальність дослідження зумовлена потребою підвищення надійності зв'язку в безпілотних мережах Flying Ad Hoc Network, де традиційні протоколи маршрутизації не враховують якість каналу та швидку зміну топології. Мета роботи полягала у розробленні інтелектуальної системи прийняття рішень, здатної адаптивно вибирати маршрут передавання даних відповідно до стану радіоканалу. Для досягнення мети застосовано методи нечіткої логіки, математичного моделювання, імітаційного експерименту та порівняльного аналізу ефективності маршрутизації. У ході дослідження створено модель нечіткої експертної системи, що оцінює якість зв'язку за параметрами відношення сигнал/шум, відстанню між вузлами та показниками шуму, формує базу правил типу «якщо – то» (IF-THEN) і визначає оптимальний шлях передачі – прямий або через ретранслятор. Експериментальні результати показали, що запропонована система підвищує коефіцієнт доставлення пакетів Packet Delivery Ratio до 99 %, тоді як у базових алгоритмів він становив лише 90 %. Середня затримка передачі зменшилася з 80 до 50 мілісекунд, а кількість розривів з'єднання знизилася з 0,2 до 0 випадків на хвилину. Встановлено також, що система зберігає стабільність мережі за умов коливання відношення сигнал/шум, забезпечуючи плавне перемикання маршрутів без надлишкового протоколового трафіку. Застосування нечіткої логіки дозволило враховувати невизначеність радіосередовища й проактивно реагувати на зниження якості сигналу, попереджаючи обриви з'єднань. Практична цінність роботи полягає у можливості інтеграції розробленої системи в мережеві модулі дронів для забезпечення надійної маршрутизації в умовах високої мобільності – зокрема, у військових, пошуково-рятувальних і цивільних застосуваннях

Ключові слова: Flying Ad Hoc Network; нечітка логіка; адаптивна оцінка лінку; надійність зв'язку; затримка; продуктивність мереж