

PRACTICAL ASPECTS OF CREATING A DATA TRANSMISSION SYSTEM FOR CONTROLLING UNMANNED SURFACE VEHICLES IN UNSTABLE COMMUNICATION CHANNELS

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Abstract. The study presents the development and verification of an adaptive data transmission system for controlling unmanned surface vehicles (USVs) in unstable communication channels. The work aims to overcome the limitations of existing technologies, which include LTE networks and satellite systems that fail to deliver stable service quality for USV remote control operations. The proposed adaptive routing algorithm evaluates communication channel status through three vital indicators, which include delay, packet loss, and availability. The algorithm selects the best channels according to changing weight parameters. Experimental results confirmed a significant reduction in data transmission delays, stable real-time video streaming with a delay of 1–4 seconds, and a reduction in packet loss to below 2 %. In addition, the system implements the use of modern video coding standards (e.g., H.265) and secure VPN channels, which increase bandwidth efficiency and the level of cybersecurity. The results confirm the practical suitability of the proposed system for USV operation in real marine conditions, as well as its potential for use in critical scenarios that require stable, low-latency communication.

Keywords: adaptive data transfer, unmanned vehicles, handling, maneuvering, navigation safety, communication channels, course control, routing algorithm, delay optimization, loss reduction, data packets, operational efficiency, status monitoring, 5G integration, predictive machine learning models.

INTRODUCTION

Unmanned Surface Vehicles (USVs) have become widely used in various industries and defense applications. Their versatility is due to a combination of high autonomy, navigation accuracy, and the ability to perform tasks in difficult and potentially dangerous conditions where the use of manned vessels is economically or safety unjustified. One of the major aspects of their efficiency is the reliance on communication mechanisms, which provide real-time data exchange and facilitate the distant or self-governing control functions.

Despite progress in satellite technology and wireless networks, data channels for USVs remain vulnerable to bad weather, congested networks, and interference in areas of heavy ship traffic, which results in delays, packet losses, and communication disconnections, significantly lowering the reliability of important operations, including video streaming, remote control, and autonomous navigation. Thus, the development of very reliable and adaptive communication solutions is the only way to assure the uninterrupted operation of USVs in the highly dynamic marine locations.

With the development of data transmission technologies and the growth of mobile operators and satellite communications infrastructure, the need for a reliable communication system to control unmanned surface vehicles in unstable data links is increasing. Such systems are essential for efficient and secure remote control, especially when streaming live video and maintaining stable communication with mobile objects. However, current IP networks, which were not initially designed for online video transmission, face challenges such as packet loss and significant latency. These factors critically impact broadcast quality of experience (QoE), especially for streams compressed to modern standards such as H.265, which depend on link stability and bandwidth.

Moreover, LTE mobile networks and satellite systems like Starlink might run into impediments such as intermittent sporadic disconnectivity and exacerbated-latencies bursts from packet transmissions. In the backdrop of a situation of uncertainty, whereby perhaps signals from mobile companies would be erratic, and where amplitude variations on the dish would disallow constant quality in the provision of digital services; this situation would necessitate ad-hoc channel hopping solutions to ensure video transmission is successfully spread across channels with the least possible latency.

Current research principally focuses more on improving network variables or increasing the stability of individual links in the com-mon mesh scenario. Not much of the work has been directed at the design on a routing-system based on multiple adaptive channels for UAVs which consider their environmental dynamic nature. In the sense of technical overhand, this article attempts to fill in that space by introducing a new algorithm offers an absolute optimization for ad-hoc transmission of data.

RELATED WORK

The current approaches to maintaining quality of communication with unmanned surface vehicles (USVs) on unstable data links include a wide range of techniques to minimize latency, packet loss, and link resilience. Previous research in USV communication can be categorized into three main areas: signal and interference robustness, adaptive algorithms for dynamic environments, and multi-channel approaches for fault tolerance. This categorization allows us to identify the gaps the proposed research aims to address.

In 2023, 3GPP presented an overview of support for the NR (New Radio) standard for USVs, emphasizing the adaptation of modern networks for seamless data transmission and control in a multi-channel network environment [1]. However, current technologies are under-researched in terms of adaptive channel selection under dynamic network variability, which requires further development of algorithms that can take into account the parameters of current network conditions to improve quality of service (QoS) and quality of experience (QoE) perception.

Research in video streaming emphasizes the critical impact of packet loss and delay variations on real-time quality. In [2], they considered how delay and packet loss variations reduce the QoE perception, which is especially relevant for USV streaming, where delays can become critical for the operator. Other works, such as [3], have proposed a QoE prediction model for multimedia services but have not provided an adaptive solution capable of dynamically adjusting to changes in network conditions. In contrast, [4] proposed an approach to improve QoE in wireless

network conditions using multiple coding, improving data transmission reliability in a variable bandwidth network.

The predictive and adaptive QoE control techniques for video streaming proposed by [5] allow for estimating the current network parameters and adjusting the routing parameters based on changes in transmission conditions. However, their adaptation framework does not cover specialized solutions for multi-channel routing in drone environments, where latency and packet loss during control are critical. At the level of specific network technologies, [6, 7] discusses the importance of minimizing control channel delay for remote control systems, showing that LTE and 4G networks pose significant limitations regarding stability and latency. However, their research focuses more on theoretical estimates of delay parameters rather than the practical use of adaptive routing algorithms for continuous drone control on unstable communication channels [8].

Routing optimization and traffic management techniques, such as the one proposed in [9], offer solutions that provide fault tolerance and security to networks under multi-criteria routing conditions. However, applying these solutions to unmanned aerial vehicle (UAV) scenarios is limited because they do not provide dynamic adaptation to real-time channel changes, which is critical for link stability in drone control systems [10, 11]. The authors in [12] also proposed complex optimization methods for self-organizing networks, which can theoretically improve adaptive routing control, but requires refinement for practical application under high load conditions and frequent link switching.

Based on the analysis of existing research, it can be seen that although many approaches have been developed to improve QoE and reduce data transmission latency, a significant gap remains in adaptive routing for highly loaded, unstable links used for drone data transmission [13–16]. This study seeks to address this gap by proposing an algorithm capable of dynamically accounting for changes in network parameters and adjusting data routes to ensure high stability and quality of real-time drone communications [17, 18]. Additional research offers unique approaches to improve security and resilience in complex environments. In [19], radar-based methods for object detection and recognition on water were investigated, highlighting the importance of reliability and accuracy of data transmission in unstable environments similar to those observed in control. [20, 21] developed polarization-based approaches to improve object identification and safety under challenging data transmission conditions applicable to tasks. In [22] investigated the energy efficiency of motors, which can further contribute to the sustained operation of drones, especially in environments where channel quality and reliability are critical to maintain control.

Reliable two-way communication with UAVs is critical for efficient control and data exchange. Several studies have focused on energy efficiency and system optimization. For example, the energy efficiency improvement of electric motors in autonomous vehicles was investigated in [23], and energy-efficient positioning systems for multi-purpose ships were proposed in [26]. In [24], a simulation-based method for predicting the seaworthiness of vessels applicable to UAV performance modeling was developed, and operational efficiency in transportation projects was evaluated [25].

Communication protocols have also been a key area of research. Shi et al. reviewed protocols for UAV inspections [27] and studied optimal power allocation methods [28]. In [29], UAV swarm architecture for efficient data routing. Sources [30–35] are devoted to current research in the field of unmanned aerial vehicles and

marine technologies. The research focuses on designing two-way communication systems for UAVs and optimizing secure communication through full-duplex systems and RIS technology and implementing solar power solutions on commercial vessels for emergency fire protection. The combination of these research studies shows progress in multiple fields which include communication protocols and cyber security and energy sustainability and intelligent control systems.

Intelligent control systems and methods for enhancing maneuverability and optimizing energy consumption in transportation [36–39] are crucial for developing practical solutions in UAV control. Data security and threat countermeasures [40, 41] are vital for ensuring sustainable communication and defense in unmanned systems. The extension of mathematical tools and intelligent approaches for dynamic object control [42, 43] applies to UAV navigation. Threat analysis, obstacle avoidance techniques, safety of cargo carriage and operator interaction [44, 45] form a basis for creating reliable and safe UAV control systems. Sources [46–49] highlight key aspects of unmanned aerial vehicle development: inertial navigation accuracy, control system improvements, and spatial route optimization, demonstrating that current research is focused on improving the reliability and efficiency of drones in challenging operating conditions.

An analysis of existing research shows that, despite the significant number of approaches proposed to improve quality of service (QoS) and reduce data transmission delays, there remains a significant gap in adaptive routing for highly loaded and unstable channels used in unmanned aerial vehicle data transmission systems.

This paper attempts to address this shortcoming by developing an algorithm that can dynamically respond to changes in network parameters and adjust information transmission routes, ensuring high stability and quality of communication in real time.

The proposed approach covers the transmission of control signals, telemetry, and streaming video with minimal delays, and also implements the protection of information flows using VPN tunneling. As part of the study, experiments were conducted on the selection of routers and the optimization of their parameters in order to improve the efficiency of data transmission under conditions of unstable communication channels.

MATERIALS AND METHODS

Problem statement and system description

Modern data transmission systems for unmanned surface vehicle (USV) control require a stable connection that delivers control signals, telemetry, and streaming video. These data types have different quality of service requirements: minimum latency and high accuracy are critical for control signals while streaming video requires high bandwidth and minimal packet loss to preserve image quality. The basis of the proposed system is the use of two communication channels: LTE (4G) mobile networks and Starlink satellite system. LTE provides a wide coverage area and affordable data rates but is prone to instability in conditions of congestion or weak signal. Starlink, on the other hand, provides a more stable connection through low-orbit satellites, but is subject to signal fluctuations due to antenna movement and view limitations. In real-world conditions, none of these technologies can guarantee constant quality of service (quality of service), which requires the development of solutions that adapt to the cur-

rent state of the network. In real-world conditions, none of the existing wireless technologies can guarantee consistent Quality of Service (QoS), which necessitates the development of adaptive solutions capable of responding to the current state of the network. In particular, instability is observed in LTE mobile communications, especially in areas with heavy traffic or insufficient signal coverage. According to research results, typical problems include connection drops and increased data transmission delays. Fig. 1 shows that the time it takes to switch between channels can be tens of seconds, which significantly complicates the stable control of unmanned surface vehicles (USVs) and real-time data transmission.

Ping was selected as a universal tool for latency assessment due to its availability across all network environments. Although ICMP traffic can be deprioritized, our parallel measurements using UDP-based tools confirmed that ICMP delays closely mirrored the latency experienced by video and telemetry data (Fig. 1).

```
Reachable Hosts:
Reply from 192.168.89.1: bytes=32 time=74ms TTL=63
Reply from 192.168.89.1: bytes=32 time=73ms TTL=63
Reply from 192.168.89.1: bytes=32 time=75ms TTL=63
Reply from 192.168.89.1: bytes=32 time=76ms TTL=63
Reply from 192.168.89.1: bytes=32 time=80ms TTL=63
Reply from 192.168.89.1: bytes=32 time=75ms TTL=63

Unreachable Hosts:
Reply from 10.10.89.1: Destination host unreachable.
Reply from 10.10.89.1: Destination host unreachable.
Reply from 10.10.89.1: Destination host unreachable.
Reply from 10.10.89.1: Destination host unreachable.
Reply from 10.10.89.1: Destination host unreachable.
Reply from 10.10.89.1: Destination host unreachable.
Reply from 10.10.89.1: Destination host unreachable.
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Reply from 10.10.89.1: Destination host unreachable.
Reply from 10.10.89.1: Destination host unreachable.
Reply from 10.10.89.1: Destination host unreachable.
Reply from 10.10.89.1: Destination host unreachable.
```

Fig. 1. Example of Ping command passing when switching between WAN links on Teltonika RUT series routers

Similar problems occur with the frequency of connection checking at routers, as shown in Fig. 2. Here, we can see that the minimum connection check time in the standard configuration of Teltonika routers is limited to 30 seconds, which is insufficient for rapid adaptation to changing channel conditions.

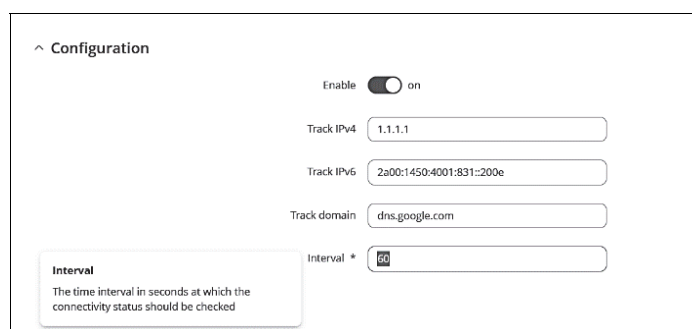


Fig. 2. Connection state polling interval parameter for RUT routers

The challenge is to design a data transmission system that minimizes latency, maintains stable transmission quality, and provides data protection. To achieve this, the following approaches are used:

- video stream tuning using modern compression algorithms (e.g., H.265) to reduce data volume without significant quality loss;
- VPN tunnels (e.g., based on OpenVPN or WireGuard) to encrypt transmitted data and improve its security;
- adaptive data routing using algorithms for assessing the current channel state (latency, packet loss, availability) to select the optimal channel in real-time.

Optimize equipment settings, including IP camera and router parameters, to coordinate bandwidth allocation, optimize encoding settings, and ensure stable transmission.

Thus, the proposed communication system focuses on complex signal processing to balance minimum latency, connection stability, and high data rate even in unstable channel conditions.

VPN encryption introduced an additional latency of 20–50 ms. We optimized MTU size, used hardware-accelerated encryption, and implemented fast packet re-routing to mitigate this. WireGuard was selected over OpenVPN due to its lower latency, simpler codebase, and faster handshake processes, making it more suitable for UAV real-time communication.

Data transfer methods and technologies

Distributed multi-channel data transmission methods and adaptive routing algorithms ensure stable communication with unmanned platforms even under unstable communication channel conditions. Such approaches minimize the impact of delays, packet loss, and communication failures by distributing information flows across multiple channels.

The developed communication system implements parallel data transmission through various media, including mobile networks (LTE) and the Starlink satellite system. For example, control commands can be transmitted via LTE, while video streams can be transmitted via Starlink and this distribution increases communication reliability and reduces the risk of complete loss of communication.

In addition, dynamic traffic distribution is applied, taking into account the current characteristics of the channels, such as bandwidth and latency. Switching between channels is based on specific criteria – latency, packet loss percentage, and channel availability.

Thus, if the delay in the LTE network exceeds the acceptable threshold (for example, 400 ms), the system automatically redirects traffic via Starlink. To improve the efficiency of the switching process, adaptive algorithms are used that take into account the weighting coefficients of each channel, which change dynamically depending on its current state.

A comparative analysis of various data transmission technologies has shown that the use of outdated communication standards, in particular 2G and GPRS, is accompanied by significant signal delays – from 124 to 2819 ms, which effectively makes it impossible to use them for tasks that require real-time data processing (Fig. 3).

```

C:\Users\Dr.Vad>ping 192.168.94.30 -t

Pinging 192.168.94.30 with 32 bytes of data:
Request timed out.
Reply from 192.168.94.30: bytes=32 time=825ms TTL=62
Reply from 192.168.94.30: bytes=32 time=124ms TTL=62
Reply from 192.168.94.30: bytes=32 time=154ms TTL=62
Reply from 192.168.94.30: bytes=32 time=108ms TTL=62
Reply from 192.168.94.30: bytes=32 time=100ms TTL=62
Reply from 192.168.94.30: bytes=32 time=551ms TTL=62
Reply from 192.168.94.30: bytes=32 time=2819ms TTL=62
Request timed out.
Request timed out.
Reply from 192.168.94.30: bytes=32 time=1841ms TTL=62
Request timed out.
Request timed out.
    
```

Fig. 3. Ping delays when modems operate in 2G and GPRS modes

In contrast, modern LTE modems that support channel aggregation significantly increase bandwidth. Fig. 4 shows that using an LTE Cat.6 modem allows you to combine 15 MHz and 10 MHz bands for a total channel width of up to 25 MHz. This improves link reliability and data transfer rates, especially for video streaming.

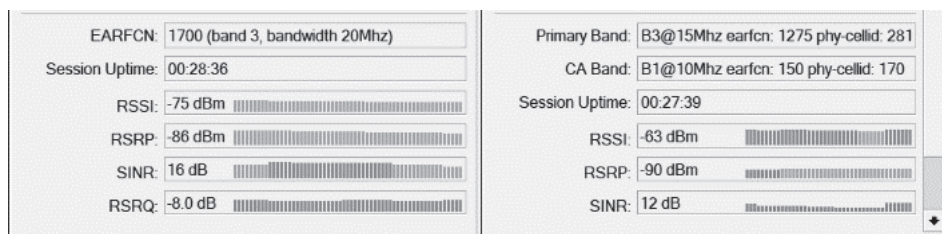


Fig. 4. Example of using channel aggregation (CA Band) on LTE Cat.6

Distributed data transmission and adaptive routing techniques allow optimal utilization of available communication channels, reducing latency and improving data transmission stability. This is especially important for drone control, where communication quality is critical to mission performance. The illustrations illustrate the advantages of modern data transmission technologies and the need to abandon outdated standards.

Adaptive channel selection algorithm

An adaptive routing algorithm ensures stable communication under unstable channel conditions by dynamically analyzing channel state and adjusting their priorities based on current parameters. The algorithm takes into account the following key indicators (Table 1).

Table 1. Key metrics used in the adaptive channel selection algorithm and their impact on prioritization

Metric	Description	Impact on Priority
Latency (Ping)	Measures the average response time of packets for each channel. If latency exceeds 400 ms, the channel receives a lower priority	Higher latency decreases the channel's priority
Packet Loss	Tracks the percentage of lost packets on each channel. Channels with high packet loss are excluded from routing or assigned penalty coefficients	High packet loss results in reduced priority or exclusion from routing
Channel Availability	Assesses the availability of the connection. If the channel is temporarily unavailable, its priority is automatically decreased	Unavailable channels are deprioritized or excluded
Weight Coefficients	Dynamically adjusted based on the channel's performance. Channels with low latency and minimal packet loss receive the highest priority	Optimized channels are prioritized based on their performance metrics

The logic of the algorithm is as follows:

1. Initialization. The initial channel weights are set (e.g., $W_1 = 3$, $W_2 = 4$, $W_3 = 5$).
2. Checking packet losses. If the losses exceed the acceptable threshold, a penalty factor (e.g., +20) is added to the channel weight.
3. Checking the delay. If the delay is within the threshold, the channel is checked further; if the delay is above the threshold, a penalty factor (+10) is added to the weight.
4. Channel selection. The channel with the lowest penalty (highest priority) is selected from the available ones.

Fig. 5 shows the block diagram of the adaptive channel selection algorithm. It includes the following steps:

- initial initialization of parameters;
- packet loss analysis on the channel;
- ping delay verification;
- dynamic change of weighting coefficients;
- selection of the optimal channel for routing.

The advantage of this approach is that using this algorithm allows for reducing the switching time between channels. Minimize data loss in unstable conditions and Provide reliable traffic routing for drone control tasks.

The algorithm, in turn, can be implemented as a software script to run on routers that support dynamic routing, such as MikroTik devices. Its flexibility allows it to adapt to real-time network changes, making it a versatile solution for data communication systems.

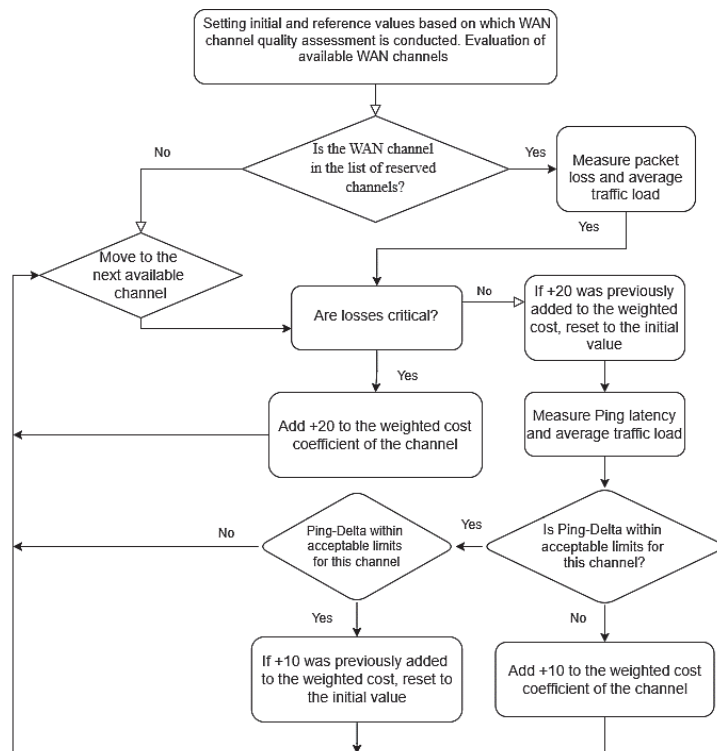


Fig. 5. Block diagram of the data link state quality assessment algorithm for traffic routing

Experimental validation and results

The experimental results confirm the effectiveness of the proposed methods for adaptive control of data links. The main objectives of the tests included reducing latency, improving link stability, and improving link capacity. Prior to system optimization, significant data transmission quality problems were observed.

Fig. 6 shows an example of unoptimized traffic where high latency and irregular link failures resulted in unstable network performance. Under high load conditions, packet losses reached up to 15–20%, making it impossible to control the drone in real time steadily.

Interface List													
Interface	Interface List	Ethernet	EoIP Tunnel	IP Tunnel	GRE Tunnel	VLAN	VXLAN	VRRP	VETH	MACsec	MACVLAN	Bonding	LTE
Name	Type	Actual MTU	L2 MTU	Tx	Rx	Tx Packet (p/s)	Rx Packet (p/s)						
R	ether1	Ethernet	1500	1596	13.6 Mbps	8.6 Mbps	1 768	1 433					
	ether2	Ethernet	1500	1596	0 bps	0 bps	0	0					
	ether3	Ethernet	1500	1596	0 bps	0 bps	0	0					
R	l2tp-out1	L2TP Client	1450		0 bps	0 bps	0	0					
R	lo	Loopback	65536		0 bps	0 bps	0	0					
R	lte1	LTE	1500		0 bps	0 bps	0	0					
R	lte2	LTE	1500		8.6 Mbps	9.5 Mbps	1 280	1 393					
X	wireguard1	WireGuard	1420		0 bps	0 bps	0	0					
X	wireguard2	WireGuard	1420		0 bps	0 bps	0	0					
R	wireguard3	WireGuard	1420		7.9 Mbps	411.9 kbps	841	540					

Fig. 6. Example of data traffic values with non-optimized IP camera settings

Significant improvements were observed after the implementation of adaptive channel selection algorithms. Fig. 7 demonstrates the optimized Ping latency values, which have been reduced to 50–150 ms. This meets real-time requirements and ensures reliable control of the USV. Packet loss was minimized to less than 2%, confirming the effectiveness of adaptive routing.

```
C:\Users\Dr.Vad>ping 192.168.92.30 -l 1380 -f -t

Pinging 192.168.92.30 with 1380 bytes of data:
Reply from 192.168.92.30: bytes=1380 time=107ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=98ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=95ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=114ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=115ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=129ms TTL=61
Request timed out.
Reply from 192.168.92.30: bytes=1380 time=118ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=103ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=102ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=117ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=114ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=91ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=125ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=94ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=114ms TTL=61
Request timed out.
Reply from 192.168.92.30: bytes=1380 time=91ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=115ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=119ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=110ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=91ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=94ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=125ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=133ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=92ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=208ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=117ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=91ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=115ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=118ms TTL=61
Reply from 192.168.92.30: bytes=1380 time=125ms TTL=61

Timestamp: 17:41:49
```

Fig. 7. Ping delay values in installed communication channels after implementation of recommendations and optimization of equipment settings

The results of the experiments showed the following:

1. Delay reduction on all channels was reduced by 60–70% on average, which ensured stable connection;
2. Stability improvement as the use of adaptive algorithms allowed to maintain stable data transmission even in conditions of high network load;
3. Optimization of throughput capacity. Due to dynamic routing, the load was evenly distributed between the channels, reducing the congestion of individual network segments.

These results confirm that implementing the proposed methodology of adaptive channel selection and equipment optimization can provide high-quality communication in drone control systems. These improvements prepare the system for real-world applications where link stability and minimum latency are critical.

RESULTS AND DISCUSSION

The study's results confirmed the effectiveness of the proposed adaptive routing system for data transmission in USV's control systems. The main achievements are significantly reducing data transmission delays, ensuring stable communication even under unstable network conditions, and minimizing packet loss. During

the experiments, it was possible to achieve video transmission with a delay of 1 to 4 seconds, corresponding to real-time requirements. The adaptive routing system proved its ability to dynamically select the optimal channel based on current network parameters such as latency, packet loss, and link availability. The fast switching between channels maintained high reliability and quality of service, making the system suitable for real-world applications. Baseline latency without our algorithm ranged from 8 to 12 seconds due to frequent retransmissions and unstable routing. Achieving 1–4 seconds with our adaptive routing is optimal for UAV operations in challenging network conditions, ensuring timely control and acceptable video quality.

Nevertheless, the work identified areas for further improvement. For example, it is possible to integrate channel state prediction techniques using machine learning algorithms, allowing for advance determination of optimal routes based on historical data and current trends. In addition, the use of modern video encoding technologies, in particular H.266/VVC, allows for a significant reduction in the amount of data transmitted without any noticeable loss of image quality. An additional area of optimization is the use of hardware with increased computing power, in particular routers with faster processors, which ensures more efficient traffic processing and routing.

Analysis of video recordings showed that in the absence of a developed algorithm, frame freezes, image pixelation, and increased latency due to packet loss are observed. After implementing the algorithm, the number of missed frames is significantly reduced, artifacts almost disappear, and the video stream remains stable even with changing network characteristics.

The developed system can be adapted to new communication standards, in particular 5G, which will provide higher bandwidth and minimal delays. This makes the proposed solution flexible and suitable for integration into scalable data transmission networks.

CONCLUSIONS

This paper presents a study aimed at the development and experimental verification of a data transmission system for controlling unmanned surface vehicles under conditions of unstable communication channels. The main limitations of modern communication technologies (LTE, Starlink) in their use for USV control are investigated. Special attention is paid to the impact of latency, packet loss, and link instability on quality of service (QoS). An algorithm that dynamically evaluates the state of available communication channels based on parameters such as delay, packet loss, and availability is proposed and described. A system of penalty coefficients is realized, allowing to correct channels' priority operatively.

The proposed system was tested on actual data, which showed that the use of adaptive routing allows for significantly reduced delays (up to 1–4 seconds) and minimized packet losses (up to less than 2%). Modern compression algorithms (H.265) and VPN tunnels were used to improve the security of transmitted data. This ensured more efficient utilization of channel bandwidth. A comparative analysis has shown that the enhanced data transmission system has evidently out-classed the non-enhanced one especially in the main indexes of connection stability, speed, and immunity against noise. Transmission delays, packet loss, and signal fluctuations, crucial variables for a reliable command of unmanned surface

vehicle (USV) activities, were minimized due to fine-tuning of the transmission parameters. The proposed architecture has shown resilience against environmental stress and channel instability, which shows its practical potential. The future direction could be integration of intelligent adaptation mechanisms specifically involving real-time channel status assessment in predictive machine learning models and linking next-generation communication technologies (5G) for elevating USV communication to the next level.

REFERENCES

1. "NR Support for UAVs," *3GPP*. 2023. Available: <https://www.3gpp.org/technologies/nr-uav>
2. J. Frnda, M. Voznak, L. Sevcik, "Impact of packet loss and delay variation on the quality of real-time video streaming," *Telecommunication Systems*, 62(2), pp. 265–275, 2016. doi: <https://doi.org/10.1007/s11235-015-0037-2>
3. L. Sevcik, M. Voznak and J. Frnda, "QoE prediction model for multimedia services in IP network applying queuing policy," in *International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS 2014)*, Monterey, CA, USA, 2014, pp. 593–598, 2014. doi: <https://doi.org/10.1109/SPECTS.2014.6879998>
4. Farouk Boumehrez, Radhia Brai, Nouredine Doghmane, Khaled Mansouri, "Quality of experience enhancement of high efficiency video coding video streaming in wireless packet networks using multiple description coding," *Journal of Electronic Imaging*, 27(1), 013028, 2018. doi: <https://doi.org/10.1117/1.JEI.27.1.013028>
5. M. Taha, A. Canovas, J. Lloret, A. Ali, (2020). A QoE adaptive management system for high definition video streaming over wireless networks. *Telecommunication Systems*, vol. 77, pp. 63–81, 2021. doi: <https://doi.org/10.1007/s11235-020-00741-2>
6. A. Kutins, D. Brodnevs, "Determination of delay parameters in 4G LTE cellular mobile networks," *2022 Workshop on Microwave Theory and Techniques in Wireless Communications (MTTW)*, Riga, Latvia, 2022, pp. 62–67. doi: <https://doi.org/10.1109/MTTW56973.2022.9942617>
7. D. Brodnevs, A. Kutins, "Requirements of end-to-end delays in remote control channel for remotely piloted aerial systems," *IEEE Aerospace and Electronic Systems Magazine*, vol. 36, no. 2, pp. 18–27, 2021. doi: <https://doi.org/10.1109/MAES.2020.3039853>
8. S.L. Volkov, V.V. Skachkov, V.I. Pavlovich, V.V. Chepkiy, "Information-entropy indicator of state quality for parametric systems in multi-criteria evaluation tasks," in *Proceedings of the Conference on Development Trends of Convergent Networks: Post-NGN, 4G and 5G Solutions*, pp. 23–27. Kyiv: State University of Telecommunications, 2016.
9. O. Lemeshko, O. Eremenko, O. Nevzorova, *Flow models and routing methods in infocommunication networks: Fault tolerance, security, scalability*. Kharkiv: Kharkiv National University of Radioelectronics, 2020. doi: <https://doi.org/10.30837/978-966-659-282-1>
10. "H.264 vs. H.265: Which Should You Use?" *Accsoon*, 2024. Available: <https://accsoon.com/explore/h264-vs-h265-which-should-you-use/>
11. "IP camera streaming guide: How to setup an IP camera," *Ant Media*, 2024. Available: <https://antmedia.io/ip-camera-streaming-guide-how-to-setup-an-ip-camera/>
12. A.V. Markovsky, G.N. Vlasenko, "Ensuring global internet access: Realities, prospects, and challenges," in *Proceedings of the Conference on Development Trends of Convergent Networks: Post-NGN, 4G and 5G Solutions*, pp. 30–34. Kyiv: State University of Telecommunications, 2016.
13. "Legal Terms," *Starlink*, 2024. Available: <https://www.starlink.com/legal/documents/DOC-1400-28829-70>

14. M. Uhrina, J. Frnda, L. Sevcik, M. Vaculik, "Impact of H.264/AVC and H.265/HEVC compression standards on the video quality for 4K resolution," *Advances in Electrical and Electronic Engineering*, 12(4), pp. 421–428, 2016. doi: <https://doi.org/10.15598/aeee.v12i4.1216>
15. L. Nguyen, H.T. Nguyen, "Mobility based network lifetime in wireless sensor networks: A review," *Computer Networks*, vol. 174, 107236, 2020.
16. S. Kurdiuk et al., "Development of a high-reliability hybrid data transmission system for unmanned surface vehicles under interference conditions," *Drones*, 9(3), 174, 2025. doi: <https://doi.org/10.3390/drones9030174>
17. Y.V. Klymash, O.M. Shpur, M.V. Kaidan, "Complex optimization method for routing information flows in self-organized networks," *Bulletin of Lviv Polytechnic National University*, pp. 76–87, 2018. Retrieved from: <https://science.lpnu.ua/sites/default/files/journal-paper/2018/jun/13512/12.pdf>
18. "Bitrate and its place in video surveillance," *World Vision*, 2024. Available: <http://worldvision.com.ua/articles/bitreyd-i-ego-mesto-v-videonablyudenii>
19. "IP camera bandwidth calculator: Formula, example & tips," *Reolink*, 2024. Available: <https://reolink.com/blog/ip-camera-bandwidth-calculation/>
20. D. Korban, O. Melnyk, O. Onishchenko, S. Kurdiuk, V. Shevchenko, T. Obniavko, "Radar-based detection and recognition methodology of autonomous surface vehicles in challenging marine environment," *Scientific Journal of Silesian University of Technology. Series Transport*, vol. 122, pp. 111–127, 2024. doi: <https://doi.org/10.20858/sjsutst.2024.122.7>
21. M.S. Stetsenko et al., "Polarization-based target detection approach to enhance small surface object identification ensuring navigation safety," *System Research and Information Technologies*, no. 2, pp. 35–51, 2024. doi: <https://doi.org/10.20535/SRIT.2308-8893.2024.2.03>
22. O. Melnyk et al., "Full overlap ship security model: An integrative approach to ship-board equipment information security," *E3S Web of Conferences*, 501, Article 02002, 2024. doi: <https://doi.org/10.1051/e3sconf/202450102002>
23. Y. Volyanskaya, S. Volyanskiy, O. Onishchenko, S. Nykul, "Analysis of possibilities for improving energy indicators of induction electric motors for propulsion complexes of autonomous floating vehicles," *Eastern-European Journal of Enterprise Technologies*, vol. 2, no. 8 (92), pp. 25–32, 2018. doi: <https://doi.org/10.15587/1729-4061.2018.126144>
24. O. Melnyk, S. Onyshchenko, O. Onishchenko, O. Shcherbina, N. Vasalatii, "Simulation-based method for predicting changes in the ship's seaworthy condition under impact of various factors," *Studies in Systems, Decision and Control*, vol. 481, pp. 653–664, 2023. doi: https://doi.org/10.1007/978-3-031-35088-7_37
25. O. Melnyk, M. Malaksiano, "Effectiveness assessment of non-specialized vessel acquisition and operation projects, considering their suitability for oversized cargo transportation," *Transactions on Maritime Science*, vol. 9, no.1, pp. 23–34, 2020. doi: <https://doi.org/10.7225/toms.v09.n01.002>
26. O. Melnyk et al., "Fundamental concepts of deck cargo handling and transportation safety," *European Transport - Trasporti Europei*, issue 98, article 1, 2024. doi: <https://doi.org/10.48295/ET.2024.98.1>
27. L. Shi, N.J. Hernández Marcano, R.H. Jacobsen, "A review on communication protocols for autonomous unmanned aerial vehicles for inspection application," *arXiv preprint*, 2021. doi: <https://doi.org/10.48550/arXiv.2111.06714>
28. S. Nasrollahi, S.M. Mirrezaei, "Toward UAV-based communication: Improving throughput by optimum trajectory and power allocation," *EURASIP Journal on Wireless Communications and Networking*, vol. 2022, article no. 9, 2022. doi: <https://doi.org/10.1186/s13638-022-02087-6>
29. X. Chen, J. Tang, S. Lao, "Review of unmanned aerial vehicle swarm communication

- architectures and routing protocols,” *Applied Sciences*, 10(10), 3661, 2020. doi: <https://doi.org/10.3390/app10103661>
30. T. Ulutaş, O. Avcı, E.C. Akar, B. Köksal, Y. Kalkan, “Simple design and implementation of two-way communication system through UAV,” *Balkan Journal of Electrical and Computer Engineering*, vol. 11, issue 1, pp. 61–70, 2023. doi: <https://doi.org/10.17694/bajece.1115408>
 31. H. Lai et al., “Optimization of full duplex UAV secure communication with the aid of RIS,” *Drones*, 7(9), 591, 2023. doi: <https://doi.org/10.3390/drones7090591>
 32. L. García Rodríguez, L. Castro-Santos, M.I. Lamas Galdo, “Feasibility and limitations of solar energy integration in merchant ships: A case study on fire detection systems,” *Journal of Marine Science and Engineering*, 13(5), 991, 2025. doi: <https://doi.org/10.3390/jmse13050991>
 33. S.K. Khorasani, B.S. Ghahfarokhi, N. Movahhedinia, “UAV-assisted small base station ON-OFF switching in 6G cellular networks considering backhaul energy consumption,” *Computer Communications*, 241, 108253, 2025. doi: <https://doi.org/10.1016/j.comcom.2025.108253>
 34. G. Kou et al., “Intelligent UAV swarm key agreement survey: Systematic taxonomy, cryptographic automaton and quantum resistance,” *Internet of Things*, vol. 34, 101720, 2025. doi: <https://doi.org/10.1016/j.iot.2025.101720>
 35. S. Aggarwal, I. Budhiraja, S. Garg, G. Kaddoum, B.J. Choi, M.S. Hossain, “A blockchain-based secure path planning in UAVs communication network,” *Alexandria Engineering Journal*, vol. 113, pp. 451–460, 2025. doi: <https://doi.org/10.1016/j.aej.2024.10.078>
 36. S. Zinchenko, V. Kobets, O. Tovstokoryi, P. Nosov, I. Popovych, “Intelligent System Control of the Vessel Executive Devices Redundant Structure,” in *CEUR Workshop Proceedings*, vol. 3403, paper 44, 2023. Available: <https://ceur-ws.org/Vol-3403/paper44.pdf>
 37. V. Kobets, I. Popovych, S. Zinchenko, P. Nosov, O. Tovstokoryi, K. Kyrychenko, “Control of the Pivot Point Position of a Conventional Single-Screw Vessel,” in *CEUR Workshop Proceedings*, vol. 3513, paper 11, 2023. Available: <https://ceur-ws.org/Vol-3513/paper11.pdf>
 38. O. Fomin, A. Sulym, I. Kulbovskiy, P. Khozia, V. Ishchenko, “Determining rational parameters of the capacitive energy storage system for the underground railway rolling stock,” *Eastern-European Journal of Enterprise Technologies*, vol. 2, no. 1 (92), pp. 63–71, 2018. doi: <https://doi.org/10.15587/1729-4061.2018.126080>
 39. A.O. Sulym, O.V. Fomin, P.O. Khozia, A.G. Mastepan, “Theoretical and practical determination of parameters of on-board capacitive energy storage of the rolling stock,” *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, no. 5, pp. 79–87, 2018. doi: <https://doi.org/10.29202/nvngu/2018-5/8>
 40. O. Melnyk, S. Kuznichenko, O. Onishchenko, “Impact of AIS manipulation on shipping safety and strategic countermeasures,” *Lex Portus*, 10(4), pp. 31–39, 2024. doi: <https://doi.org/10.62821/lp10403>
 41. V.V. Yakovenko, N.I. Furmanova, I.M. Flys, O.Y. Malyi, O.Y. Farafonov, H.V. Moroz, “Determination of the generalized optimality criteria for selecting civilian shelter facilities from attacks by ballistic (cruise) missiles and kamikaze drones in urbanized areas,” *System Research and Information Technologies*, no. 3, pp. 25–43, 2024. doi: <https://doi.org/10.20535/SRIT.2308-8893.2024.3.02>
 42. A.A. Gurskiy, A.V. Denisenko, A.E. Goncharenko, “Expansion of the mathematical apparatus of discrete-continuous networks for the automation of their synthesis procedures,” *System Research and Information Technologies*, no. 2, pp. 93–99. doi: <https://doi.org/10.20535/SRIT.2308-8893.2024.2.07>
 43. S.V. Melnykov, P.M. Malezhyk, A.S. Gasanov, P.I. Bidyuk, “Methodological aspects of operative control system intellectualization for dynamic objects,”

- System Research and Information Technologies*, no. 4, pp. 44–57, 2022. doi: <https://doi.org/10.20535/SRIT.2308-8893.2022.4.04>
44. Y. Koskina, S. Onyshenko, O. Drozhzhyn, O. Melnyk, “Efficiency of tramp fleet operating under the contracts of affreightment,” *Scientific Journal of Silesian University of Technology. Series Transport*, vol. 120, pp. 137–149, 2023. doi: <https://doi.org/10.20858/sjsutst.2023.120.9>
45. I. Burmaka, I. Vorokhobin, O. Melnyk, O. Burmaka, S. Sagin, “Method of prompt evasive maneuver selection to alter ship’s course or speed,” *Transactions on Maritime Science*, vol. 11, no. 1, pp. 1–9, 2022. doi: <https://doi.org/10.7225/toms.v11.n01.w01>
46. A. Sotnikov, A. Tanciya, O. Lavrov, “Calculating method of error calculations of the object coordination by means of conducting platform free inertial navigation systems of an unmanned aerial vehicle,” *Advanced Information Systems*, vol. 2, no. 1, pp. 105–110, 2018. doi: <https://doi.org/10.20998/2522-9052.2018.1.20>
47. A. Podorozhniak, Y. Volotskov, O. Shevtsova, “Drone’s Control System Research,” *Advanced Information Systems*, vol. 2, no. 3, pp. 97–101, 2018. doi: <https://doi.org/10.20998/2522-9052.2018.3.16>
48. D. Voloshyn, V. Brechko, S. Semenov, “Method of an unmanned aerial vehicle composition route in space,” *Advanced Information Systems*, vol. 5, no. 4, pp. 26–33, 2021. doi: <https://doi.org/10.20998/2522-9052.2021.4.04>
49. O.M. Melnyk et al., “Enhancing shipboard technical facility performance through the utilization of low-sulfur marine fuel grades,” *Journal of Chemistry and Technologies*, vol. 32, no. 1, pp. 233–245, 2024. doi: <https://doi.org/10.15421/jchemtech.v32i1.297916>

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ПРАКТИЧНІ АСПЕКТИ СТВОРЕННЯ СИСТЕМИ ПЕРЕДАВАННЯ ДАНИХ ДЛЯ КЕРУВАННЯ БЕЗПЛОТНИМИ НАДВОДНИМИ АПАРАТАМИ В УМОВАХ НЕСТАБІЛЬНИХ КАНАЛІВ ЗВ’ЯЗКУ/ С.В. Курдюк, О.М. Мельник, О.А. Онищенко, С.М. Волянський, В.А. Шевченко, Б.М. Алексейчук

Анотація. Представлено розроблення й верифікацію адаптивної системи передавання даних для керування безкіпажними надводними апаратами (USV) в умовах нестабільних каналів зв’язку. Працю спрямовано на подолання обмежень наявних технологій, зокрема мереж LTE та супутникових систем, які не завжди забезпечують стабільну якість сервісу під час дистанційного керування USV. Запропоновано адаптивний алгоритм маршрутизації, що здійснює дина-

мічне оцінювання стану каналів зв'язку за ключовими показниками: затримкою, втратою пакетів та доступністю — і визначає оптимальні канали з урахуванням змінних вагових коефіцієнтів. Експериментальні результати підтвердили суттєве скорочення затримок передавання даних, стабільну трансляцію відео в реальному часі із затримкою 1–4 секунди та зниження втрат пакетів до рівня нижче 2%. Крім того, у системі реалізовано використання сучасних стандартів відеокодування (наприклад, H.265) та захищених VPN-каналів, що підвищує ефективність використання пропускної здатності та рівень кіберзахисту. Отримано результати, що підтверджують практичну придатність запропонованої системи для експлуатації USV у реальних морських умовах, а також її потенціал для застосування у критично важливих сценаріях, які потребують стійкого зв'язку з низькою затримкою.

Ключові слова: адаптивне передавання даних, безпілотні апарати, керування, маневрування, безпека навігації, канали зв'язку, управління процесами, алгоритм маршрутизації, оптимізація затримок, зменшення втрат, пакети даних, потокове відео, операційна ефективність, моніторинг стану, стиснення H.265, захищені VPN-тунелі, інтеграція 5G, моделі машинного навчання, прогнозування.