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Development of a High-Reliability Hybrid Data Transmission System for Unmanned Surface Vehicles Under Interference Conditions

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Abstract: This paper discusses modern approaches to the creation of a highly reliable data transmission system for unmanned surface vehicles (USVs) operating under interference conditions. In contrast to existing solutions, an improved communication algorithm is proposed to ensure uninterrupted transmission of video, telemetry, and control signals even in highly unstable environments. The study identifies the main technical requirements for data transmission and evaluates the key parameters of the communication channel. The proposed hybrid communication system utilizes adaptive channel switching, data compression, and equipment reconfiguration, improving data transmission stability and reducing latency. A comparative analysis of existing communication technologies reveals the limitations of acoustic, optical, and radio wave systems. A conceptual architecture combining these technologies provides optimal data transmission by adapting to the environment. Experimental results confirm the effectiveness of the system, demonstrating reliable operation even with 80% packet loss in public Internet networks. The system's adaptability, low latency, and dynamic routing make it suitable for real-time USV operations, including environmental monitoring, scientific research, and search and rescue missions. Its potential extends to commercial and dual applications requiring sustained data transmission in challenging maritime environments.

Keywords: unmanned surface vehicles; data transmission; hybrid communication systems; maritime navigation; packet loss; IP routing; VPN; LTE; QoS; communication resilience

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1. Introduction

Unmanned surface vehicles (USVs) have become an important tool for ocean exploration, environmental change monitoring, and search-and-rescue and research operations at sea, to perform logistics tasks in hard-to-reach areas. Their use facilitates varied and complex technological tasks in conditions where human participation is dangerous or impossible. Due to their autonomy and adaptability to the environment, modern USVs play a key role in data collection in hard-to-reach regions, including Arctic areas, deep-sea areas, and areas with high concentrations of maritime traffic, performing the task of finding explosive objects, demining, etc., and work in other special areas. Thus, USVs are becoming increasingly important in the modern world due to their effectiveness in application in various sectors of the economy; moreover, they are often used for dual purpose, to perform specific tasks.

Modern requirements for USVs cover not only their mobility, but also their ability to transmit data in real time, which is critical for operational decision-making, so the effective operation of USVs largely depends on the stability, speed, and reliability of data transmission systems. Ensuring uninterrupted data transmission in the marine environment remains a critical challenge. Communication systems must cope with interference caused by weather conditions, variable water salinity, and limited radio waves and acoustic bandwidth. Given the high-reliability requirements, it is necessary to develop systems that can automatically adapt to changes in the environment, minimizing delays and data loss.

Recent advances in hybrid communication systems for USVs include AI to optimize data transmission. The Inspector 125 USV uses AI for real-time obstacle detection and sensor integration [1]. The aColor Project uses AI-based models for navigation and control in autonomous marine robotics [2]. AI-driven adaptive routing enhances USV communication as shown in multi-agent deep learning with reinforcement learning for USV coordination [3]. Furthermore, deep learning with reinforcement is key to AI-driven decision-making in autonomous navigation [4]. These advances promote the integration of AI in hybrid communication systems, network resilience, adaptive channel switching, and real-time optimization.

Real-time data transmission is critical to the organization of control processes of such devices, to analyze data obtained from devices, telemetry, for making operational decisions. Particular attention is drawn to ensuring stable communication in conditions where traditional data transmission channels are often unreliable. Atmospheric phenomena, artificial obstacles, deep-water environments, strong wind, interference, as well as other natural factors can significantly affect the quality of the signal, leading to its loss, delay, and bandwidth limitations. This, for example, leads to errors, or even losses, in determining the current coordinates of the USV. For high-speed surface USVs, for example, at 55 km/h, loss of communication by 3 s leads to errors in determining its place, of 45 m, which in most cases the use of USVs is unacceptable and can lead to accidents or failure in the performance of a technological task.

The main problem is related to the transmission of large amounts of information, including video data, telemetry, and control signals, due to limitations in bandwidth and unstable communication channels. Existing data transfer technologies are often not able to work effectively under such conditions, which creates significant risks for the implementation of missions assigned to the USV.

Each of the main types of information transmitted by the USV (telemetry, high-resolution video data, monitoring, control signals of individual mechanisms, etc.), has separate requirements. But in any case, the reception and transmission of these data require highly reliable and stable communication channels that can work in conditions of significant interference, including those that arise in the water environment. Modern USVs work in conditions where the quality of communication depends on numerous factors, including not only the physical properties of water and atmospheric phenomena but also the distance of data transmission and the characteristics of the communication channels used. For example, surface USVs, which, with the help of underwater vehicles, perform deep-water search missions (wireless), are limited to low bandwidth acoustic channels, while optical communication channels are effective only at short distances and in clear water. Radio waves, on the other hand, quickly fade into the underwater environment, which limits their use. Thus, the underwater environment creates significant challenges for the developers of communication systems and for high-quality navigation. Of course, for small surface USVs, it is extremely important to ensure reliable communication over long distances. The main challenges in creating such important systems nowadays are the following:

(a). Instability of communication channels. The marine environment is characterized by strong obstacles, including waves and salinity of water, atmospheric influences, and artificial obstacles, which significantly reduce the quality of the signal and sometimes lead to its distortion;
(b). The need to minimize the delay of control signals and data transmission. In cases of video transmission of the required quality and in low visibility, darkness, telemetry transmission, and control signals, a delay of more than 1–2 s can lead to serious consequences, especially during rescue operations, maneuvering, and in other difficult technological situations, when the USV is moving at high speed;
(c). The limited energy on board. USVs have a limited supply of electrical power to ensure the reliable operation of communication systems, mechanisms, and other functions.

In addition to technical challenges, the problem of USV integration into the global network of communication and data protection is relevant. This problem involves the use of satellite technology, radio wave channels, and the existing 4 G/5 G infrastructure to ensure stable long-distance data transmission. It is known that satellite communication has a high time delay (up to 600–800 ms), and radio communication systems are limited in range, especially in the marine environment. In addition, satellite communication systems such as Starlink impose artificial restrictions on the distance of use, commercial systems are quite expensive and do not always support the necessary security parameters.

The generalized problem, which is raised in the article, consists of a comprehensive analysis of existing modern data transmission systems for surface USVs, including through the underwater environment, identifying key advantages and disadvantages in the transmission of data, developing recommendations, algorithms, and solutions for improving communication technologies with USV, and experimental confirmation of decisions taken.

The purpose of this paper is to develop a highly reliable data transmission system for maritime unmanned surface vehicles (USVs) that provides uninterrupted transmission of video, telemetry, and control signals under conditions of significant interference.

To achieve this goal, it is very important to solve the following scientific problems:

1. To determine the technical characteristics of modern data transmission systems and analyze their effectiveness in real-world operating conditions;
2. Propose a new communication system algorithm that combines the benefits of various technologies to ensure the stability and energy efficiency of the USV;
3. Experimentally confirm the proposed new communication algorithm.

The development of an effective data transmission system is an important task, the solution of which will help to increase the reliability of various missions of surface USV, increasing the level of their adaptability to changing environmental conditions. This will help to solve important practical tasks in the field of maritime security, environmental monitoring and scientific research.

While this work explores the potential of hybrid communication solutions for USVs, it primarily focuses on QoS management in high-speed surface networks utilizing Starlink technology. The discussion of underwater and alternative surface communication links is included as part of a broader perspective on future integration but is not directly analyzed in this study.

2. Analysis of Recent Studies

2.1. General Methods and Principles of Communication in Unmanned Technologies

In general, data transmission systems for unmanned navigation vehicles are defined as key to modern marine technologies. A review of freely available sources of information and the literature shows that major research in this area focuses on three main areas: acoustic, optical, and radio wave communication and data transmission technologies [5–9].

In order to evaluate the performance of the proposed system, we compared it with recent hybrid communication systems including Kongsberg solutions (2022), Starlink maritime communication (2023), and artificial intelligence optimized dynamic switching networks developed under DARPA initiatives (2024). Table 1 summarizes key performance metrics for these systems compared to our proposed approach.

Table 1. Key performance metrics of SOTA hybrid systems.

System	Data Rate (Mbps)	Latency (ms)	Packet Loss (%)	AI Optimization
Kongsberg (2022)	10–200	100–500	5–15	No
Starlink Maritime (2023)	50–350	30–120	<5	Yes
DARPA Adaptive Routing (2024)	100–600	10–150	<3	Yes
Proposed Hybrid System	50–500	100–300	<5	No (future work)

Acoustic systems are used for underwater communication due to their ability to work at long distances (up to 10 km). The authors of [5] demonstrate the stability of the functioning of such systems even in difficult conditions such as a deep-water environment. The main advantage of acoustic technologies is their ability to overcome obstacles in the water environment. However, the main limitation remains low bandwidth, which rarely exceeds 10 Kbps. This limits the use of acoustic systems to transmit large amounts of telemetry and monitoring data, real-time video, or high-resolution images. For surface USV such a connection is significantly limited for various reasons. In general, acoustic systems ensure the stability of the signal at sufficiently large distances, while optical and radio-wave channels allow for increased speed of transmission in local areas.

Acoustic communication is significantly affected by environmental factors such as thermal layers, salinity gradients, and underwater obstacles, which cause refraction and interference. Studies have shown that even small temperature variations can alter the propagation path of acoustic waves, leading to signal degradation [10,11].

Optical communication systems in USV provide significantly higher transmission speeds (up to 1 Gbps) and are effective in near-surface conditions of use or in clear water. Various works, for example [6], show that optical channels are promising for local USV missions, where the transmission distance does not exceed 100 m; however, the effectiveness of such systems is reduced in muddy water or at long ranges. Modern developments in the field of laser communication are aimed at overcoming these limitations, but this technology is still in the testing stage. Optical communication is most effective at night or in deep water where sunlight does not interfere. However, modern laser-based systems can mitigate daylight interference by using specific wavelength filtering and adaptive signal modulation techniques.

Radio wave technologies [7] are used to transfer data between USV and ground stations, and other devices. Radio transmission of data through a water medium is limited by the high absorption of radio waves by water, limiting their use. Of course, the use of LTE and 5GGi standards for communication on the surface provides new opportunities but the stability of the signal depends on weather conditions and obstacles. Other work also indicates that the use of ultra-low frequency communication signals may partially solve this problem, but this requires significant energy resources for the USV.

At high speeds, the Doppler effect introduces frequency shifts in radio and acoustic signals, potentially reducing synchronization accuracy and increasing data errors. Advanced Doppler compensation techniques are used to mitigate these effects in real-time USV operations.

Existing technologies for data transmission in harsh marine environments have significant limitations. Acoustic communication provides a range of up to 10 km, but its bandwidth (up to 10 kbps) is extremely low, making it ineffective for video streams and complex telemetry data. Optical communication (up to 1 Gbps) works at distances of up to 100 m but is prone to degradation in turbid water. Radio wave communication (up to 100 Mbps) is limited by signal absorption by water and atmospheric interference. To address these shortcomings, a hybrid system combining different technologies is proposed. It uses adaptive channel switching algorithms and load balancing to ensure reliable data transmission while minimizing interference.

Table 2 shows a comparison of the major data transmission technologies in terms of key metrics such as communication range, bandwidth, immunity to interference, and power consumption.

Table 2. Comparison of data transmission technologies.

Technology	Range (km)	Data Rate	Interference Resistance	Power Consumption	Frequency Range
Acoustic Communication	Up to 10	Up to 10 Kbps	High	Low	1–100 kHz
Optical Communication	Up to 0.1	Up to 1 Gbps	Low (murky water)	Medium	450–1550 nm (visible to near-infrared)
Radio Wave Communication	Up to 5	Up to 100 Mbps	Medium	High	2.4 GHz, 5 GHz, and LTE bands (600 MHz–3.8 GHz)
Hybrid Systems	Up to 10	Up to 1 Gbps	High	Medium	-

One of the promising directions is the development of hybrid communication systems that combine acoustic, optical, and radio wave technologies. Studies demonstrate the effectiveness of hybrid communication for data transmission under different conditions. For example, a Kongsberg Maritime (2020) study [8] shows that the combination of acoustic and optical channels allows for high transmission speeds over short distances and signal stability over long distances. This approach allows for the adaptation of the communication system to change in the environment, particularly in muddy water or in the presence of obstacles.

Modern research also covers areas of energy optimization by data transmission systems. The use of data compression algorithms and adaptive control of communication channels allows a significant reduction in the energy consumption for information transmission. The authors in [5] show that the integration of such algorithms into hybrid systems contributes to the extension of the battery life of the USV by 20–30%.

It should be noted that technological limitations remain relevant for all types of communication systems. Unmanned missions require significant investments in the development of acoustic and laser systems, and surface operations require stable satellite communications, which can be achieved by using the existing networks of operators operating in the area of the mission. To overcome these challenges, multi-level adaptive data transmission systems are needed, capable of quickly adapting to environmental conditions and ensuring a balance between transmission speed, signal stability, and energy consumption.

Thus, the analysis of literary sources shows that none of the existing technologies is universal for all multi-faceted operating conditions of USV. The development of integrated solutions that combine the advantages of various technologies remains a priority in the field of marine research, and the most simple and effective in use are satellite systems and mobile telephone systems.

2.2. Communication Systems with Remote Moving Objects (Drones) Based on Available Internet Access Channels

With the rapid development of data rates through the infrastructure of mobile telephone and satellite operators, the existing infrastructure is increasingly used to control a variety of USVs and other types of drones [12], via the transmission of a streaming video through real IP networks, which were not originally created to transmit video images online [13]. For example, drone operators need to obtain acceptable quality video for broadcasting, which will be sufficient for further use [13,14]. The quality of streaming video of the current H.265 encoding standard also depends on the loss of data packets [15]. At present, there are practical problems with the speed of data transmission, bandwidth, and speed of data transmission channels from a moving object is actually limited to existing channels [16,17]. For control signals, unmanned vehicles have already been investigated and there are recommendations for the parameters of delay of such signals [18]. The first attempts to formalize and develop recommendations for delays in signals acceptable for remote control of USV are known (for example, they were set and described in the MIL-F8785 C standard [19]). Practical studies are very important, which not only fulfil these recommendations for the management of USV but also organize the transmission of video data from the drone (where the amount of traffic is orders of magnitude higher), receive practical results of management within the existing LTET communication channels through the Starlink satellite communication system.

The experiment, which is presented further in this article, deals with the practical aspects of creating a communication system with remote moving objects (including USVs of different types and purposes), using available Internet access channels for simultaneous transmission of control signals, telemetry, and video transmission from the USV. In the process of establishing a connection with a moving object, the quality of the system state is evaluated. This evaluation occurs within the defined parameters of the connection to ensure communication with the moving object under conditions of situational uncertainty. To ensure reliable data transmission, the proposed system integrates secure VPN-based communication channels. The methodology includes an analysis of several tunnelling options, comparing the performance of standard VPN solutions with optimized configurations. The impact of VPN on latency and QoS was measured using controlled scenarios, as shown in Table 3.

Table 3. Comparison of the results achieved in the course of experimental studies.

No.	Parameter/Factor	Standard Settings (Possible Range)	Experimental Results
1	Administration of VPN server	No (Hamachi service not supported)	YES
2	Delay in video transmission	20–120 s	1–6 s
3	Average traffic from USV IP cameras	8–10 Mbps	3 Mbps
4	Number of VPN tunnelling options	1	3
5	Average delay in Starlink VPN channel	200 ms	120 ms
6	Average channel transition time (including VPN tunnel reinstallation)	60 s	20 s
7	Time to return to priority communication channel	20 s	1–2 s

The response time of the system during channel switching was analyzed to evaluate its suitability for real-time applications. The evaluation included measuring the transition time between the priority and secondary communication channels, with and without VPN reinitialization. The average switching time was significantly reduced by applying the optimized VPN configuration, as shown in Table 3. Quality of Service (QoS) was evaluated by monitoring packet loss, bandwidth fluctuations, and system latency under different network conditions. The performance comparison of different VPN configurations showed that the optimized hybrid system improved the stability and reduced packet loss.

3. Main Research Material

In the information and communication networks, there are many options for traffic routing [20,21]. To ensure reliable data transmission, we propose a multi-layer hybrid system architecture, which consists of three key levels:

- Physical Layer. Includes acoustic modules, radio frequency transmitters (LTE, 5 G), and optical communication modules;
- Network Layer. Manages adaptive channel switching, VPN tunnelling, and traffic load balancing;
- Protocol Layer. Implements QoS optimization and minimizes latency to improve data transmission efficiency.

Figure 1 illustrates the architecture of the hybrid data transmission system, demonstrating the interaction between its components.

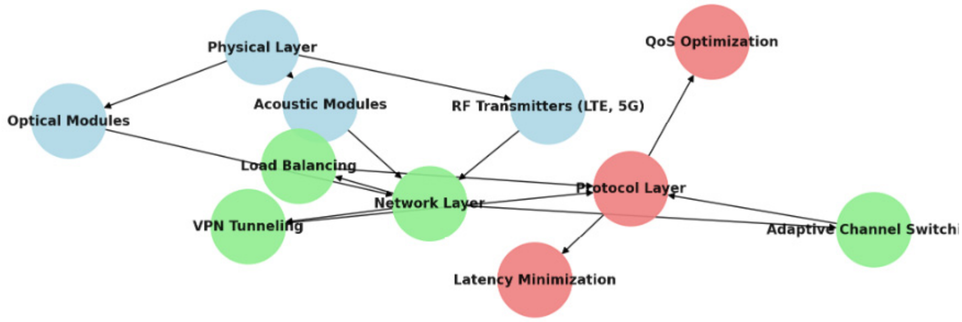

Figure 1. Architecture of the Hybrid Data Transmission System for USVs.

In order to increase the likelihood of exchanging and transmitting information from/to moving objects (including USV) that do not have guaranteed connections to the Internet or to a control station, usually in typical routers with several external WAN channels, in small networks, the following three solutions (either their complete or limited combination) are used:

- Redirect or switch traffic from one interface (WAN channel) to another, or several other WAN channels. This is performed in cases where the primary WAN-channel interface does not respond or has signs of a communication break (meaning a physical or logical gap);
- Parallel, duplicated multipath data traffic transmission over multiple WAN channels;
- Proportionally distributed multi-road traffic across multiple WAN channels. For example, 60% of data packets are sent through one interface (channel), and 40% are sent through another at this time.

The selection of the necessary equipment [17,18,20,21] is justified by configuring various system settings to achieve optimal performance, reliability, and stability. These configurations are designed to balance the influence of three critical factors:

(a). delay (in data transmission and video display);
(b). bandwidth (channel bandwidth);
(c). availability of the communication channel.

The data routing algorithm includes the following steps:

1. Determining the state of the communication channels: estimating the current delay, throughput and packet loss rate on each channel;
2. Weighting assignment: using penalty factors to account for deviations from acceptable values;
3. Optimal Channel Selection: automatically switching to channels with minimum delay and packet loss;
4. Adaptive System Tuning: real-time reconfiguration of weights when channel characteristics change.

The input data are evaluated based on the types of traffic relevant to USV (unmanned surface vehicle) operations. The considered traffic categories are listed in Table 4.

Table 4. Traffic categories and prioritization for USV communication.

Traffic Type	Data Source	Characteristics	Priority
Online Video Transmission from USV	2–3 IP cameras	High data rate, continuous streaming, low latency	Highest (Consumes largest portion of traffic)
Control Signal Transmission to USV	Remote control stations	Low data volume, highly time-sensitive, minimal delay	Critical (Navigation and operational safety)
Telemetry Data Transmission from USV	Onboard sensors and systems	Moderate data volume, periodic or event-triggered	Important (Monitoring and diagnostics)

Although video transmission consumes the largest amount of bandwidth, control signals are prioritized to ensure operational safety and immediate responsiveness in critical scenarios.

By assessing these types of traffic, bandwidth is allocated, data flows are prioritized, and transmission protocols are optimized to ensure reliable USV performance and mission success. Critical data streams, such as control signals and telemetry, are prioritized due to their impact on operational stability, while video transmission is managed to prevent network congestion.

3.1. Evaluation of Traffic Generation from Devices to the Internet

Experimental results indicate that, in Roaming mode, the Starlink upload speed varies between 4 and 6 Mbps under good environmental conditions. It is necessary to adjust settings so that Upload stream from video cameras, on average, is not higher than 4 Mbps. Modern IP-video cameras have a resolution of 2 Mpx and above and form multiple streams of video transmission at the same time. However, in most cameras, there are settings that reduce the resolution of the main stream to 1 Mpx (Table 5).

Table 5. Experimental Data.

Communication Technology	Range (km)	Average Latency (ms)	Packet Loss (%)	Bandwidth (Mbps)
Acoustic	10	500–1200	15–30	0.01–0.02
Optical	0.1–0.5	<50	<1	500–1000
Radio Wave	5	50–200	5–10	10–100
Hybrid (Proposed)	10	100–300	<5	50–500

The results confirm that the proposed hybrid system provides an optimal balance between communication range, transmission stability, and bandwidth while minimizing packet loss and latency.

During the experiments, it was found that the quality acceptable for the operator was achieved by transmitting video images from a moving USV at a frame rate of 12 to 15 frames per second, with a resolution ranging from 640×480 to 1280×720 pixels. Evaluate the traffic generated by IP cameras with the following input parameters:

- Channel capacity of 3 Mbps;

- The H.264 and H.265 video compression algorithms were applied based on standard camera configurations. H.264 provides broader compatibility and low computational requirements, making it suitable for real-time applications with limited processing power. In contrast, H.265 provides higher compression efficiency, reducing bandwidth consumption while maintaining video quality, making it ideal for bandwidth-constrained environments.

H.265 is preferred for traffic minimization due to its superior compression efficiency, reducing bandwidth usage by up to 50% compared to H.264 while maintaining video quality. It is known [21] that the preference for the volume of traffic is better to give the compression protocol H.265, as it provides better compression. But when switching from channel to channel, it has been determined that the recovery time of the video transmission in the case of H.265 may be 1–2 s longer than in the case of H.264 cameras. The two cameras transmit data simultaneously over three independent channels, providing redundancy and load balancing. The following values for IP cameras are taken:

To calculate the bitrate for USV camera streams, three key parameters were taken into account: resolution, frame rate, and compression ratio. Based on these parameters, the following approximate bitrate values were used for H.265 video encoding:

- Camera 1: 1280 × 720 to 1920 × 1080 resolution, main stream: 1280 × 720, 15 fps, H.265–0.7 Mbps per camera; Secondary stream: 640 × 480, 10 fps, H.265–0.3 Mbps per camera;
- Camera 2: 640 × 480 resolution, main stream: 640 × 480, 15 fps, H.265–0.4 Mbps.

Total bitrate calculation:

- Main stream (2 cameras): 1280 × 720, 15 fps = 0.7 Mbps × 2 = 1.4 Mbps;
- Secondary stream (2 cameras): 640 × 480, 10 frames per second = 0.3 Mbps × 2 = 0.6 Mbps;
- Primary stream (1 camera): 640 × 480, 15 frames per second = 0.4 Mbps;
- Total cumulative bitrate: 1.4 Mbps + 0.6 Mbps + 0.4 Mbps = 2.4 Mbps.

The required bandwidth for OpenVPN transmission was calculated as 2.6 Mbps = 1.08 × 2.4 Mbps, ensuring sufficient capacity for video data streams. The selection of cameras and their configuration directly impact bandwidth requirements. In our setup, adaptive encoding dynamically adjusts stream quality to optimize performance under varying network conditions.

This calculation ensures efficient bandwidth allocation while maintaining high video quality for mission-critical operations. The overhead costs of data transmission were calculated. We used encryption (encapsulation) of video traffic through a VPN tunnel. This gives overhead in the range from 4 to 10%, depending on the type of VPN protocol. Note that the WireGuard VPN protocol adds headers to each data pack of 60–80 bytes. Thus, if necessary, in a standard data package of 1500 bytes, we have a payload of 1420 bytes and the Wireguard protocol encryption overhead is 80/1420 × 100 = 5.6%.

For the OpenVPN VPN protocol, we have the following. OpenVPN header—60–80 bytes, AES encryption header—16 bytes, Message Authentication code—16 bytes. Total 112 bytes. The payload is 1388 bytes and the OpenVPN encryption overhead is 112/1388 × 100 = 8%.

3.2. Simple Option to Create a Tunnel Without Encryption

A VPN tunnel was created using a combination of protocols L2TP + GRE. The main overhead costs of this option are as follows:

- L2TP (Layer 2 Tunnelling Protocol). The L2TP header adds about 4–12 bytes. The UDP header adds 8 bytes. The IP header adds 20 bytes;
- GRE (Generic Routing Encapsulation). GRE header adds 24 bytes.

Thus, the total overhead for L2TP + GRE is approximately 56–64 bytes. The remaining payload is 1500 − 64 = 1436 bytes. The overhead of tunnelling using the L2TP + GRE option is (64/1436) = 0.044 × 100% = 4.4%, and in general, we obtain a speed of 2.4 Mbps × 1.08 = 2.6 Mbps.

With selected resolutions and settings from three IP cameras and using H.265 video compression protocol, the expected total transmission flow will be up to three Mbps, which is required to solve the problem of creating the system.

If H.264 video streaming compression is used, the video transfer traffic is about 30% higher than H.265. In the course of the experiments, recommendations on the use of RTCP video data stream and minimizing the size of the data cache in the settings of the media player were tested [21]. The disadvantage of this option is that in practice, after changing and switching data channels, a constant part of the lag of the video image is obtained.

Table 6 contains the standards of mobile network data transmission, which are present in Ukraine.

Table 6. Standards for data transmission of mobile networks.

Generation of Networks	Standards	Basic Characteristics	Range of Real Data Rates in the Network
2.5 G	GPRS, EDGE (2.75 G), 1xRTT	Internet, exchange of media reports, batch data transfer	In the first phase 115 kbit/s, in the second—384 kbit/s.
3 G	WCDMA, CDMA2000, UMTS	The first broadband network, support for video stream transmission, Free data transfer (multimedia, text), Internet	From 2 Mbps to 14 Mbps.
3.5 G	HSPA, HSDPA, HSPA+ (3.75 G)	Increased speed for incoming and outgoing Internet traffic	From 14 Mbps to 42 Mbps.
4 G	WiMAX, LTE	IP-based protocol focusing on massive volume transfer information, real broadband mobile network	From 30 Mbps to 800 Mbps.

Table 6 shows summary data of possible maximum speeds in different generations of data transmission standards of mobile operators from GSM GPRS to LTE [21–23].

The difference between 3 G and LTE technology, in relation to equipment, is that 3 GH technology usually uses a fixed channel width of 5 MHz, and the equipment built on LTE 4 G technology is supported by MIMO technology. Hence, it is possible to use Scalable Bandwidth and organize strip transmission channels of 5, 10, 15, and 20 MHz. If the LTE modem supports channel aggregation technology, higher data rates will be available. Thus, we define that it is permissible to use equipment that operates in standards not only of standard 4 G, but also in standards 3.5 Gta even and 3 G. The main we found during the use of RUTs was the slow switching from one type of communication channel to another type of communication channel, and the operating system of the router RUT "does not see" that the WireGuardVPN (v0.5.3) server tunnel was installed. It was determined that the industrial products of the RUT200 Teltonika Series routers, RUT500 have a long time of reconnecting the data and video communication routing [22–25]. Due to limitations of the software of the manufacturer, it is impossible to reduce the period of the Internet connection check interval to less than 30 s.

The results of the research are presented based on the implementation of both dynamic and static data traffic routing protocols. These protocols were evaluated in terms of their effectiveness in ensuring stable communication and minimizing data transmission delays. It was found that using the default settings of a variety of routers and IP cameras resulted in transmission delays that ranged from 10 to 40 s when two IP cameras were installed on a USV.

We estimated the criticality of the video delay in the management of USVs, relative to the path passed at a constant speed (s = v × t, where s—distance travelled, m, v—speed USV, m/s, t–time delay of transmission in video image, c, from the real location of the device). At cruising speed of 40 km/h (11.1 m/s), we found that for 10 s of communication delay the difference in the real location (actual position) and the feed received from the IP cameras video is more than 100 m (s = 11.1 m/s × 10 s = 111 m).

Figure 2 shows the values that are obtained without optimizing the video stream from IP cameras. As can be seen, the traffic of the LAN attainable port was 13.6 Mbps via the TX channel (sending) and 8.6 Mbps via the RX channel (receiving), and the traffic on the modem (interface) LTE2 was 8.6 Mbps by TX 9.5 Mbps by RX. During the experiments, it was also found that the Starlink moving object system (40 km/h) gives the average Upload stream speed of 4–5 Mbps. Therefore, it is necessary to assess the possibility of [23–27] subsettings for those channel parameters that are available during the performance of the USV mission, that is, to make the IP-camera settings so as not to exceed the data stream of 4 Mbps.

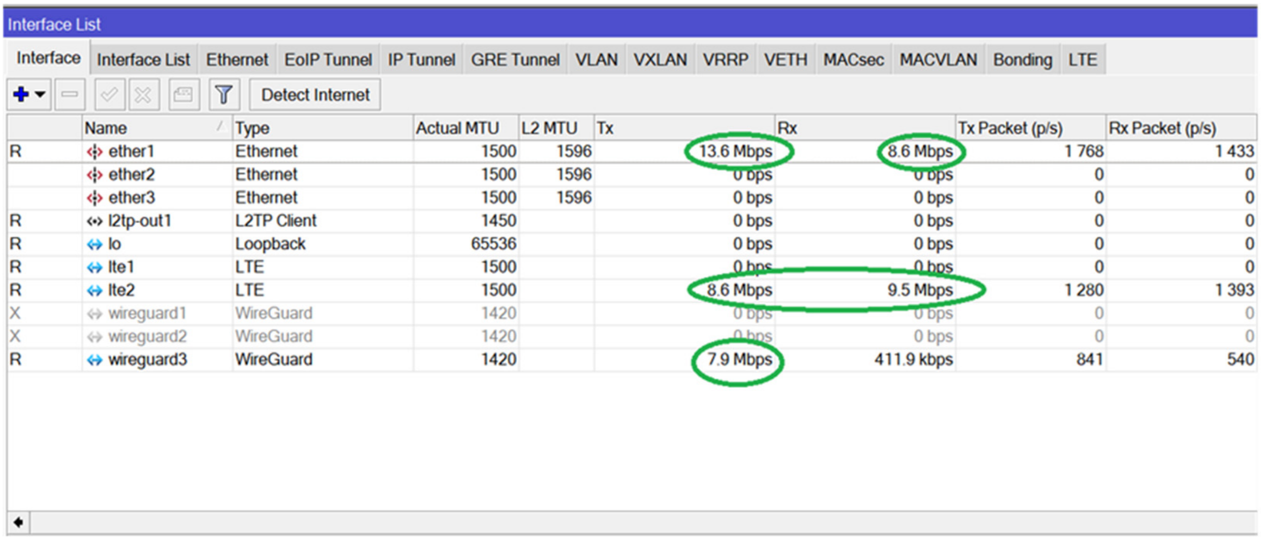

Figure 2. Examples of data traffic values in case of unoptimized settings of IP cameras.

Experiments with the study of various protocols, both dynamic routing and static routing of data traffic, showed important findings. Under conditions of situational uncertainty on unstable data transmission channels, solving the specific problem of data transmission from USV (real-time video stream from two IP cameras with minimization of video delay + telemetry) and data transmission to USV (USV management) required additional measures. These experiments highlighted the need to create a software script. This script would analyze the current situation and evaluate the performance of existing WAN channels of the selected equipment.

An algorithm for data delivery optimization was designed based on the available equipment capabilities, functionalities, and operational limitations. Table 7 outlines the key parameters considered in algorithm development, ensuring efficient routing and adaptive traffic management.

Table 7. Available options and functions on the router to use and/or measure for developing a technical solution algorithm.

No.	Functionality and/or Parameter	The Possibility of Using the Decision-Making Algorithm for the Use of WAN Channel	Ability to Measure or Read the Current Value	The Ability to Set the Value of the Parameter Relative to Which to Make Decisions in the Algorithm	Description
1	Ping—delay in the channel	Yes	Yes. Calculation (formula)—definition of the average value	Yes	Time delay in data transmission, ms
2	Loss of packages	Yes	Yes. Counting with formulas	Yes	Percentage of lost packets, %
3	Availability interface	Yes	Yes	Yes	Whether the interface is active (Yes/No)
4	The weighting coefficient for determining the cost for the route through a certain physical interface	Yes	Yes. Ability to read the current value	Yes	Relative priority of a channel (1–10)
5	Time to decide on availability of the DT (decision time) service or functionality	No	No	Yes	--
6	The presence of data passing through the interface	No	Yes	Yes	-
7	Hysteresis (delta tolerance) rejection received values	Yes, Ping command	No, read Ping value	Yes	-

Based on the parameters listed in Table 7, an algorithm was constructed (Figure 3) to evaluate the data traffic passing through the external WAN channel of the router by continuously monitoring key metrics such as ping delay, packet loss rate, and channel availability. Initial weight coefficients are assigned to each WAN channel based on predefined performance criteria. The algorithm measures ping delay and packet loss, assesses channel availability and applies penalties if thresholds are exceeded. The channel with the lowest weighted score is selected for primary data transmission, with automatic switching if instability is detected. Weight coefficients are reset if the channel's performance improves and stabilizes within acceptable limits.

The algorithm involves the following commands and parameters: the initial priority of using a WAN channel, the current ping value (delay signal in the channel), the average reported ping value, the permissible short-term deviation from the ping value, which is equal to delta-ping (delta-tolerance) or, the total number of packets in the current WAN-channel measurement cycle, the allowable number of packet losses in the WAN-channel, the time of the period of blocking one of the services when the parameters of all available channels exceed the permissible parameters, including or excluding the WAN-channel into the quality measurement cycle [25,26]. The simplified code to explain the work of the proposed algorithm is as follows:

1. Initial conditions:
   - Let (W_I) be the weight of the route for the channel (I) (where (I = 1, 2, 3));
   - Let (P_I) be the loss of data packets on the channel (I);

- Let (L_I), be the delay in the channel (I) measured by the ring command;
- Let (P_{{threshold}}), be the allowable threshold of packet loss;
- Let (L_{{threshold}}), be the allowable delay threshold.

2. Algorithm:
   - Initialization of the initial weighting coefficients (initial weight): [W_1 = 3, W_2 = 4, W_3 = 5];
   - Checking packet loss: [{If} P_i > P_{{threshold}}, {then} W_i = W_i + 20 {i go to next channel}];
   - Delay check: [{If} P_is less than or equal to P_{{threshold}}, {then measure} L_I] [{If} L_I > L_{{threshold}}, {then} W_I = W_I + 10];
   - Go to the next channel: [{repeat steps 2 and 3 for all I} I = 1, 2, 3].
3. Example **of constructing a system of equations:**

For each channel (i) (where (i = 1, 2, 3)):

[W_I = begin{cases} W_I+ 20, & {if} P_I > P_{{threshold}} \ W_I, & {otherwise \ \end{cases}];

[{If} P_I \ leq P_{{threshold}}, {then}];

[W_I = \ begin{cases} W_I+ 10, & {if} L_I > L_{{threshold}} \ W_I, & {otherwise \ \end{cases}].

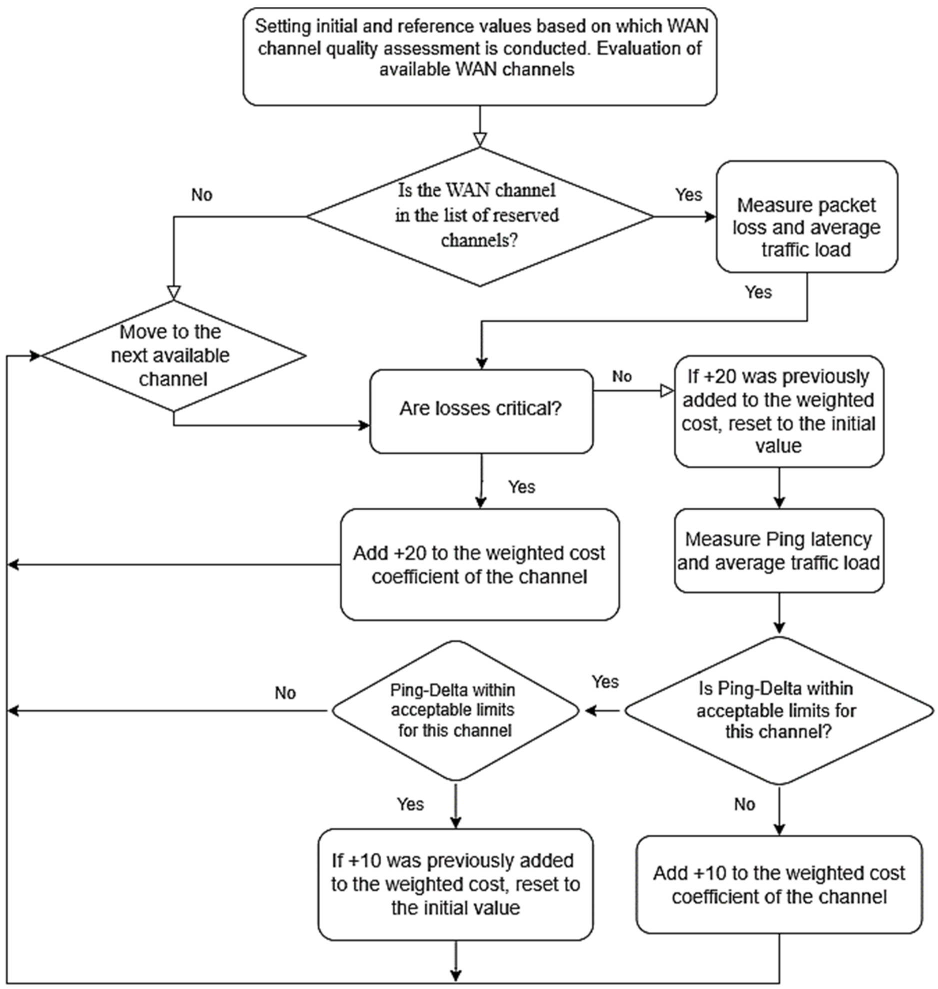

Figure 3. Decision-making algorithm in choosing the optimal channel for transmission and routing data.

Thus, the initial static routing weights will be adjusted depending on the current characteristics of the channels, which gives a more efficient control over the routing of traffic. The penalty values (10 and 20) were chosen based on empirical testing to create a balance between channel switching sensitivity and stability. Lower values led to slower reactions, while higher values caused excessive switching.

This simple algorithm allows dynamic adjustment of load coefficients of routes depending on the current characteristics of the channels, ensuring a higher priority use of channels with less packet loss and delays.

In the full script, taking into account the hysteresis (delta)—value of the delay ring, and return the initial weighting coefficients of routing the channel if the channel meets the specified initial requirements (for delay of data passage and packet loss). Only a subset of the proposed methods has been implemented in this iteration. The 'full script' refers to the complete automation framework, which includes additional optimization modules not yet deployed.

One critical aspect of USV communication is security. As cyber threats in maritime networks increase, our system integrates encrypted VPN tunnels and dynamic firewall policies to prevent unauthorized access. Future work will explore AI-based anomaly detection for real-time cyber threat mitigation.

Implementation of the proposed algorithm, according to the block of the decision-making scheme, is made using a software script for analyzing the states of WAN-channels based on the rules of static routing for routers of the Routerboard from series manufacturer MikroTik (Rīga, Latvia).

The proposed algorithm involves the methods listed below, the implementation of which is used in the full script.

1. Penalty Method. In this method to the target function are added penalty coefficients of violation of restrictions. In the event that the loss of packets or delay exceeds the permissible thresholds, the penalty coefficients are added to the weight of the route.
2. Adaptive Algorithms. These algorithms change the parameters of the system depending on the conditions. The proposed algorithm adapts the weight coefficients of the routes depending on the packet loss and delay.
3. Linear programming. Linear programming is often used to optimize routing in networks. The modified algorithm, although not strictly linear programming, uses linear weight changes depending on the conditions.
4. Heuristic Methods. Heuristic methods are often used when the exact solution is difficult or impossible to find. The proposed approach uses some heuristic elements because it uses simple rules to adjust the weight of the routes.
5. Quality of Service, QoS. In network technology, QoS methods are used to manage traffic priorities. The proposed algorithm resembles the approaches of QoS, where routes with better characteristics acquire greater priority.

Generalized conclusions and comparisons obtained by the results of practical experiments on data transmission are summarized in Table 3.

The experimental results presented in Table 3 demonstrate significant improvements in VPN performance and latency reduction. Compared to standard configurations, the proposed system achieves a 3× reduction in channel switching time and a 2× improvement in Starlink VPN delay. These findings confirm the system's robustness in real-world USV operations under high-interference conditions. Thus, it is possible to draw general conclusions from the carried-out improvements of software, experimental, and settlement studies of communication systems with USV.

Future research will focus on AI-assisted optimization for real-time channel selection, allowing the system to dynamically adapt to changing network conditions. Machine learning models can be trained to predict packet loss trends and proactively switch to more stable channels, further improving the reliability of data transmission. In addition, the scalability of the system for different types of USV missions will be analyzed to ensure compatibility with commercial, military, and scientific applications.

Efficient data transmission for USVs in challenging environments requires addressing several critical factors, including hydrometeorological conditions, energy consumption, and communication reliability. Multiple aspects critical in the domain such as hydrometeorological situations, energy demands, and assurance of communication reliability, need to be thoroughly reviewed for efficient data transmission for unmanned surface vehicles (USVs) operating under all these conditions. The results of related studies will become part of the considerations for establishing highly reliable hybrid communication channels. Adaptability of the environment: energy efficiency and reliability of communication are the main aspects for enhancing the communication systems of the USV. Onishchenko and Melnyk (2021) have emphasized hydrometeorological characteristics for real-time decisions [28,29]. For this reason, the hybrid contact systems developed should be information-based according to the methods proposed in [30] for predicting seaworthiness. Energy efficiency has been highlighted by Volyanskaya et al. (2018) as an essential factor in autonomous systems. Multi-ship operations query the emergency transfer of information across these ships using reliable low-latency communication as highlighted in [31,32].

The design and development of a highly reliable hybrid data communication system for USVs under interference conditions must utilize advanced technologies and methodologies to ensure reliable communication, safety, and environmental sustainability. Sagin et al. [33–35] in their previous studies emphasized methods by which the environmental and operational reliability of marine vessels, including the use of biofuels, can be adapted to the sustainable operation of hybrid USV power systems. Zinchenko et al. [36–38] presented intelligent control systems associated with ship devices and solutions for ship rocking prevention, emphasizing the importance of such robust data-driven control mechanisms in terms of the marine environment.

Future improvements to USV communication systems should include methods to address safety and risk management in maritime operations. As noted by Melnyk et al. (2022), the fundamental issues of maritime safety relate to the reliable deployment of USVs [39]. In addition, Melnyk et al. (2023) proposed an expert judgement-based approach to operational risk assessment, consistent with systematic risk assessment in complex environments [40].

It is reasonable that the dynamic environment of USVs makes route optimization a vital factor in their operation. Xiao et al. [41] and Huang et al. [42] proposed ways in which route optimization can benefit from local weather routing and adverse sea conditions avoidance, aspects that can be immediately borrowed as inputs for real-time path planning, as it is an integral part of USV operations in an interference-resistant environment. Continuous and secure data transmission is one of the biggest obstacles. Harish et al. [43] presented an exhaustive review article covering the last decade of maritime cybersecurity that emphasizes how important it is to protect communication links from cyber-attacks in hybrid systems.

Thus, to ensure the stability of data transmission, our system uses adaptive channel management algorithms. They analyze the environment parameters and dynamically select the optimal channel (acoustic, optical, or radio wave), minimizing the impact of interference. Importantly, the system balances the load between technologies by switching depending on the communication conditions, which allows us to maintain a stable data flow even in the presence of significant external interference.

Building on these foundations, the proposed system will utilize robust data communication protocols with real-time environmental monitoring and secure communication links to maximize the reliability and performance of USVs in harsh maritime environments.

4. Conclusions

The study emphasizes the critical role of uninterrupted communications in maritime unmanned vehicle (USV) operations. It was demonstrated that stable video transmission with an average latency of 1.2 to 4 s is achievable even on relatively unstable network links by optimizing the settings of standard IP cameras designed for both residential and industrial applications. These cameras initially have a delay of 1–1.5 s in the formation and transmission of the video stream. If all external communication channels fail or do not meet the required performance criteria, the system automatically waits for an update and reconnects to the most available channel of the global network. In the case of temporary loss of communication, the last working channel is stored in memory, which allows you to quickly reconnect to it when a working channel is found.

Reducing the overall video transmission delay is possible due to software modifications of IP cameras with inherent formation and transmission delays of 100–120 ms. This latency, previously equated to the reaction time of human vision, becomes crucial for real-time USV control. The total latency of the system, including video encoding, encryption and routing, is 250–300 ms. This is quite an acceptable range for comfortable remote control of the vehicle over long distances, enabling accurate and responsive task completion.

In scenarios using static routing based on standard Internet protocols, video and telemetry data transmission delays of up to 20–25 s when VPN tunnels are used or recovered. This corresponds to the standard values defined in the specifications of routing protocols. If the main WAN link becomes operational and meets the specified criteria for delay and packet loss, the system automatically restores its use within 1–2 s. The use of dynamic routing approach, combining non-standard and standard protocols, allows to accelerate WAN link switching and VPN tunnel recovery by 2–3 s, ensuring minimal service interruptions.

Managing a fleet of USVs or Autonomous Platforms (APs) running in parallel enables static routing while supporting a single VPN server. However, ensuring continuous connectivity with a maximum switching delay of 3–5 s requires updated dynamic routing and a dedicated VPN server for each USV. This approach facilitates parallel operation and ensures seamless remote management even when network conditions change rapidly.

Experimental results confirm the effectiveness of the system in transmitting video, telemetry, and control data over long distances, even when packet loss reaches 80%. Despite severe connectivity problems, the system maintains stable operation by dynamically switching to available channels. Its integration into USVs used for scientific research, environmental monitoring, and search and rescue missions demonstrates its practical applicability. In addition, its dual purpose in commercial operations requiring reliable and stable communications in harsh environments makes the system suitable for marine industry applications, including maritime infrastructure management, security patrols, and resource exploration.

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Abbreviations

USV	Unmanned Surface Vehicle
QoS	Quality of Service
VPN	Virtual Private Network
LTE	Long Term Evolution
WAN	Wide Area Network

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