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## Method for video data transmission at the application layer with adaptive control in an unmanned aerial vehicles network

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### ABSTRACT

Video streams transmitted from unmanned aerial vehicles are a critical source of situational information for monitoring, search-and-rescue, emergency response, and security applications. In such time-critical scenarios, the practical value of a video frame rapidly decreases after a deadline, while unmanned aerial vehicle networks are characterized by stochastic variability of delay, jitter, losses, and dynamic topology. Therefore, the problem of ensuring timely delivery of video frames through adaptive, application-layer control becomes relevant. **The object of research** is the process of video frame transmission in unmanned aerial vehicle networks under stochastic channel and routing conditions. **The subject of research** is methods and models of adaptive control of video frame delivery at the application layer, including strategy selection under deadline constraints. **The purpose of this paper** is to develop an application-layer method for adaptive transmission of video frames that increases the probability of delivery before a deadline and reduces the fraction of late-or-lost frames in unmanned aerial vehicle networks. A conceptual framework for adaptive control of video frame transmission is proposed, including a decision model for selecting transmission strategies based on observed network conditions and deadline requirements. An adaptive algorithm for per-frame strategy selection is developed, incorporating rules for retransmission limitation, buffering management, and robustness mechanisms (e.g., redundancy-based delivery). A set of evaluation metrics is defined to characterize timeliness and reliability, including the probability of on-time delivery, average delay of delivered frames, loss probability, and the late-or-lost fraction. Simulation-based assessment demonstrates that adaptive control improves deadline reliability compared to fixed transmission strategies across representative unmanned aerial vehicle network regimes.

**Keywords:** Unmanned aerial vehicle networks; video streaming; application-layer control; adaptive transmission; deadline reliability; stochastic delay; jitter; packet loss

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### INTRODUCTION

**Relevance.** The process of video data transmission in computer networks of unmanned aerial vehicles (UAVs) is characterized by increased dynamism of communication channel parameters, the stochastic nature of delays, the possibility of packet losses, and limited predictability of the network topology [1]. Under such conditions, ensuring stable and timely delivery of video information requires the use of methods capable of adapting to changes in the network state without intervention in the hardware or low-level software components of the system. One of the key issues in the development of such methods is the choice of the

OSI model layer at which it is advisable to implement control of the video data transmission process [2].

In modern UAV systems, the physical and data link layers, as a rule, are implemented in the form of closed hardware-software solutions optimized by the manufacturer for specific usage scenarios. Wireless access protocols, modulation and coding algorithms, as well as transmission-medium control mechanisms at these layers are unavailable for modification or have strictly limited configuration capabilities. Similar limitations often apply to the network layer as well, in particular to routing protocols, which in UAV networks usually operate in a semi-automatic mode and do not provide the necessary flexibility for controlling the temporal characteristics of individual data flows.

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Against this background, the application layer acts as the only layer at which the implementation of flexible and adaptive control of the video data transmission process is possible without changing the existing hardware platform or network infrastructure. It is precisely at the application layer that video frames are formed, the parameters of their transmission are determined, buffering is performed, delivery time is controlled, and decisions are made regarding the expediency of retransmission or discarding frames that have lost relevance. Thus, the application layer naturally combines information about the requirements of the video service and the current transmission conditions, which makes it the optimal environment for implementing the method of video data transmission with adaptive control.

**An overview of scientific works.** Modern studies on video data transmission in UAV networks reveal three persistent trends:

- practical systems and platforms (e.g., WebRTC) demonstrate the feasibility of low-latency video, but are often limited to empirical metrics;
- adaptive engineering mechanisms (ARQ, FEC, multipath transmission, buffer management) improve QoS, yet mostly optimize average indicators;
- analytical/stochastic models better capture uncertainty in channels and topologies, but often do not integrate full per-frame control logic with a formal objective such as  $P(T \leq T_d)$ .

In paper [3], the authors systematize that for time-critical services the decisive factors are not mean values but delay variability and unpredictable delay “spikes”. It is emphasized that these effects most frequently break real-time operation. However, the review mainly ends with recommendations to reduce delay variability, without a formal transition to frame-oriented metrics (what should be considered “on-time”) and without a clear control problem formulation where decisions are made at the frame/packet level.

Paper [4] provides a broad overview of 6G technologies (including the UAV component), where latency and reliability are identified as key KPI (Key Performance Indicator). The work also supports the relevance of our study by highlighting a systemic need for adaptation and “intelligence” in networks. Unfortunately, as a typical technology survey, it gives little concrete detail on adaptation mechanisms specifically for video frames and does not present detailed application-layer algorithms.

In paper [5], the authors propose a three-layer framework for integrating UAVs into Intelligent Transportation Systems (ITS). They also summarize

challenges such as mobility, coverage, connectivity, and QoS constraints. At the same time, as a framework-level survey, the work rarely moves to a formal evaluation of delivery time specifically for video frames. Adaptation is largely descriptive. For a scientific contribution, it is important to complement such frameworks with a quantitative problem statement, specifying which metrics are optimized and how decisions are tied to deadlines.

Paper [6] considers a graph-based stochastic model (GERT) that enables describing alternative routes/branching and random delays, and obtaining aggregated temporal delivery characteristics under uncertainty. The paper discusses typical practical limits of GERT approaches. Formally, it identifies scalability indicators and assumptions about delay distributions that may be simplified. However, it leaves unresolved how to embed realistic logic of retransmissions, buffering, and mode switching into the model so that it reproduces the behavior of real protocol stacks.

In paper [7], [21], the authors show that moving part of processing functions closer to the source reduces delay and increases responsiveness in emergency scenarios. At the same time, many edge-based approaches optimize system metrics but often do not reveal strategic behavior under network degradation. It is not specified what to do with frames when deadlines are inevitably violated, how to separate “useful” frames from expired ones, and how to avoid situations where an increase in packet loss leads to a growth in deadline violations.

The authors of paper [8] propose mechanisms to support different classes of streaming services in a V2X environment. A key idea is that traffic with different requirements should receive different network treatment. It should be noted that differentiation is often performed at the stream/class level, while for UAV video the dynamics within the stream are critical: individual frames may have different value and different deadlines. Future work should therefore move from “service class” differentiation to frame-aware policies.

In paper [9], a deadline is introduced as a central constraint for transmission planning and packet servicing. The study shows that deadline-based approaches differ significantly from optimizing average delays. However, as can be seen from this work, transport and packet-level formulations often do not account for media semantics. In addition, the impact of retransmissions and feedback on deadline satisfaction is considered only in a limited way, although this is a critical aspect for UAV video data.

In paper [10], the authors propose an application-layer ARQ for multi-source delivery of video data in a UAV network with QoS evaluation. This is one of the few works that directly studies application-layer loss recovery in a UAV environment. At the same time, the main open problem of ARQ for real-time video is that retransmissions increase delay and may turn “successfully delivered” into “delivered but too late”. Future work requires an explicit policy for when retransmissions should be prohibited or limited, and how to align ARQ with deadlines and buffering.

In paper [11], an FEC-based scheduling scheme with adaptive redundancy selection is proposed. This is useful as an “alternative class” to ARQ, since losses can be compensated without retransmissions. At the same time, FEC increases channel load and may worsen performance under low bandwidth or competing flows. The paper lacks a systematic analysis of the redundancy–deadline trade-off across different network regimes and in multi-hop UAV scenarios.

Paper [12], [22] investigates how multipath mechanisms of tunneling and path aggregation improve the stability of real-time video streaming by reducing the impact of fluctuations on a single link. However, as noted, further research should analyze not only mean delay but also the risk of violating deadlines under different correlations of delays across paths.

In paper [13], [23] a case study with field experiments is presented. WebRTC is proposed as a transport basis for achieving very low end-to-end delays in UAV-borne IoT. Differences from “classical” solutions (e.g., WebSocket) and the influence of network conditions are shown. It should be noted that case studies typically focus on demonstrating platform capabilities but have limitations; for example, a generalized policy for handling frames under network degradation is missing.

In paper [14], a web-oriented Ground Control Station with a WebRTC media server is developed for controlling multiple UAVs, access roles, and video-telemetry streams. Unfortunately, engineering prototypes often lack deep analytics. In this paper, a systematic study of delay distributions is missing, and there is no policy for flow/frame competition under deadlines.

In paper [15], the practical feasibility of long-range UAV operations using commercial LTE networks is demonstrated. Architectural solutions and measurements of system behavior are presented.

At the same time, the paper does not fully account for the fact that LTE networks have variable quality, leading to sharp spikes in delay and loss. Future studies should consider how the system should react to abrupt degradations, how to “filter” expired frames, and how to compare alternative transmission strategies under the same mean delay but different variance.

In paper [16], an adaptive routing protocol is proposed, aimed at improving route stability in a highly mobile network and enhancing delivery performance. It should be noted that routing, unfortunately, does not guarantee multimedia deadlines: even with a better route, queues, collisions, and delay peaks may occur. A promising direction is to complement adaptive routing with application-level frame control mechanisms and analyze the combined effect.

In paper [17], the authors propose an approach that accounts for energy consumption and node mobility to stabilize connectivity in a UAV cluster. This is useful for long-term missions and reducing link break frequency. However, energy-mobility optimizations may conflict with timely delivery requirements for video data (e.g., an “energy-saving” route may be slower). For multimedia, it is important to analyze the temporal usefulness of the delivered content as well.

Thus, the literature review shows that existing solutions for video transmission in UAV networks are mainly focused on platform implementations and local adaptation mechanisms (ARQ/FEC/routing), but do not provide a unified formalized approach that accounts for stochastic channel variability and video frame deadlines. This creates the need to develop an integrated frame transmission control method aimed at maximizing timely delivery and minimizing the fraction of “late or lost” frames.

**Setting objectives.** The purpose of the study is to develop an application-layer video data transmission method with adaptive control in a UAV network, capable of adjusting to changing network conditions and ensuring predictable timeliness of video information delivery under given time constraints. This will increase the fraction of frames delivered before the deadline, reduce the fraction of frames that are late or lost, and stabilize video stream operation under dynamic topology and stochastic channel variability.

To achieve this purpose, the following tasks are set:

- justify the application layer as the environment for implementing the proposed video transmission method;

- formulate the concept of adaptive control of the video frame transmission process;
- formalize the decision model within the proposed method;
- develop an adaptive video frame transmission algorithm depending on the deadline and the current network state, including rules for limiting retransmissions and managing buffering;
- integrate the application-layer video transmission method with practical video transmission protocols.

### THE APPLICATION LAYER AS THE ENVIRONMENT FOR IMPLEMENTING THE VIDEO DATA TRANSMISSION METHOD

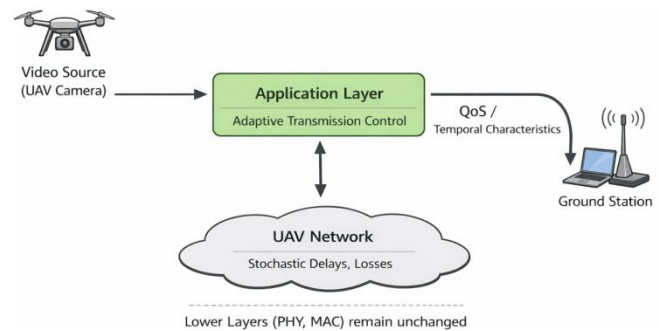
The process of video data transmission in computer networks of unmanned aerial vehicles is characterized by increased dynamism of communication channel parameters, the stochastic nature of delays, the possibility of packet losses, and limited predictability of the network topology. Under such conditions, ensuring stable and timely delivery of video information requires the use of methods capable of adapting to changes in the network state without intervention in the hardware or low-level software components of the system. One of the key issues in the development of such methods is the choice of the OSI model layer at which it is advisable to implement control of the video data transmission process.

In modern UAV systems, the physical and data link layers, as a rule, are implemented in the form of closed hardware-software solutions optimized by the manufacturer for specific usage scenarios. Wireless access protocols, modulation and coding algorithms, as well as transmission-medium control mechanisms at these layers are unavailable for modification or have strictly limited configuration capabilities. Similar limitations often apply to the network layer as well, in particular to routing protocols, which in UAV networks usually operate in a semi-automatic mode and do not provide the necessary flexibility for controlling the temporal characteristics of individual data flows.

Against this background, the application layer acts as the only layer at which the implementation of flexible and adaptive control of the video data transmission process is possible without changing the existing hardware platform or network infrastructure. It is precisely at the application layer that video frames are formed, the parameters of their transmission are determined, buffering is performed, delivery time is controlled, and decisions are made regarding the expediency of retransmission or

discarding frames that have lost relevance. Thus, the application layer naturally combines information about the requirements of the video service and the current transmission conditions, which makes it the optimal environment for implementing the method of video data transmission with adaptive control.

The conceptual placement of the application layer in the video data transmission loop in a UAV network is shown in Fig. 1. The video source, represented by the camera of an unmanned aerial vehicle, forms video frames that enter the application layer, which performs the functions of adaptive transmission control. It is at this layer that control decisions are made regarding the transmission parameters of a video frame, taking into account the stochastic characteristics of the communication channel and the temporal requirements for data delivery [18], [19].



**Fig. 1. The application layer as an adaptive control loop for the process of video data transmission in a UAV network**

*Source: compiled by the authors*

The UAV network in the diagram is presented in the form of a generalized transmission environment characterized by stochastic delays and possible data losses. The lower layers of the OSI model, in particular the physical and data link layers, are considered as unchanged and not involved in the adaptive control process. The ground station receives the video data and forms information about quality-of-service indicators and temporal characteristics of transmission, which are used as feedback for the application layer. Thus, the application layer acts as a closed-loop adaptive control system for the process of video data transmission in a UAV network.

It is important to emphasize that in the context of the application layer, the concept of a method of video data transmission is not reduced to the development of a new data exchange protocol. Instead, the transmission method is implemented as a set of algorithms and rules for controlling the delivery process of video frames, which determine

the choice of transmission strategy depending on the stochastic characteristics of the communication channel and time constraints. Such an approach makes it possible to separate the transmission control logic from the mechanisms of packet transport, ensuring compatibility with existing application-layer protocols such as RTP or RTSP, and preserving the possibility of integration with various UAV hardware platforms.

The use of the application layer as the environment for implementing the method of video data transmission is also consistent with the requirements of real-time systems, for which critical are not only the average delay values but also the probability of delivering a video frame within a specified deadline. At the application layer it is possible to directly take into account the semantics of the video stream, in particular the relevance of individual frames, allowable losses, and requirements for playback smoothness, which is impossible or extremely difficult to implement at the lower layers of the OSI model. This creates prerequisites for using stochastic models of the communication channel as a tool for forecasting and making control decisions for each video frame.

Therefore, the choice of the application layer as the environment for implementing the method of video data transmission in a UAV network is justified from the point of view of practical implementability, control flexibility, and compliance with the requirements of real-time video services. It is precisely at this layer that it is possible to effectively combine a stochastic description of the transmission process with algorithmic mechanisms of adaptive control, which constitutes the basis of the method of video data transmission with adaptive control in a UAV network proposed in this work.

### **THE CONCEPT OF ADAPTIVE CONTROL OF THE VIDEO FRAME TRANSMISSION PROCESS**

Adaptive control of the video frame transmission process in a UAV network is based on the need to ensure the temporal requirements of video information delivery under conditions of stochastic variability of communication channel parameters. Unlike traditional approaches focused on average delay values or reactive recovery of lost data, the proposed concept envisages forming control decisions based on predictive characteristics of the transmission process. This makes it possible to consider the transmission of each video frame as a separate controlled process, the result of which is

evaluated in terms of the probability of timely delivery.

The key idea of adaptive control is the use of a stochastic description of the transmission process to evaluate not only the expected delivery time, but also the probability distribution of this time. In the context of video frame transmission, this means that the decision on transmission parameters is made taking into account the probability of meeting the given deadline, and not only with a view to minimizing the average delay. This approach is especially important for real-time video services, where an overdue frame loses informational value regardless of the fact of its physical delivery.

Within the proposed concept of adaptive control, the process of transmitting a video frame is considered as a closed loop in which the state of the system is characterized by a set of stochastic parameters obtained on the basis of a mathematical model of the transmission process. Such parameters include an estimate of the mathematical expectation of delivery time, a measure of delay variability, and the probability of delivering a video frame within an allowable time interval. It is these characteristics that are used as the informational basis for forming the control action that determines the choice of the transmission strategy for the current video frame.

An important feature of the proposed concept is that control is carried out at the level of individual video frames, rather than in the form of global optimization of flow parameters. This makes it possible to promptly respond to short-term changes in the state of the communication channel and avoid the accumulation of delays characteristic of methods based on long-term averaging of quality-of-service indicators. In such a formulation, each video frame is considered as an informational object with its own time constraints, which is consistent with the nature of real-time video transmission.

Adaptive control within the framework of the concept under consideration does not envisage direct intervention in routing mechanisms or physical access to the transmission medium. Instead, control decisions affect the logic of processing and transmitting video frames, in particular the choice of the transmission mode, the admissibility of retransmission, and the expediency of discarding frames that cannot be delivered on time. Such an approach makes it possible to align the requirements for temporal delivery guarantees with the real capabilities of a UAV network under conditions of stochastic influences.

In a generalized form, the principle of forming a control decision regarding the transmission of an

individual video frame can be presented in the form of the following relationship:

$$S_k = \underset{s \in S}{\operatorname{argmax}} \mathbb{P} \{T_k^{(s)} \leq T_d\},$$

where  $S_k$  is the selected transmission strategy for the  $k$ -th video frame;  $S$  is the set of admissible transmission strategies;  $T_k^{(s)}$  is the random variable of the delivery time of the video frame when using strategy  $s$ ;  $T_d$  is the admissible deadline delivery time.

Thus, the concept of adaptive control of the video frame transmission process consists in using the stochastic characteristics of the communication channel as a basis for predictive adoption of control decisions oriented toward ensuring probabilistic time requirements of delivery. The proposed approach creates a theoretical foundation for the formalization of the rules for selecting a transmission strategy, which will be considered in detail in the next subsection when describing the formalization of control decisions based on a stochastic model of the transmission process. Further formalization of control decisions and the definition of specific transmission strategies based on the stochastic model of the transmission process are considered in the next subsection.

### FORMALIZATION OF CONTROL DECISIONS BASED ON A STOCHASTIC MODEL

The formalization of control decisions within the proposed method of video data transmission is carried out on the basis of a stochastic model of the transmission process, which makes it possible to quantitatively describe the temporal characteristics of video frame delivery in a UAV network. Such an approach provides a transition from a conceptual understanding of adaptive control to formally defined decision-making rules based on probabilistic characteristics of the transmission process.

Within the model considered in Chapter 2, the transmission of a video frame is described as a random process with a given structure of routes and stochastic delays at individual stages. The result of applying this model is the determination of the random variable of the video frame delivery time, for which the mathematical expectation, measures of variability, and the distribution function can be obtained. It is the distribution function of the delivery time that plays a key role in the formalization of control decisions, since it allows estimating the probability of meeting the specified time constraints.

The formation of a control decision regarding the transmission of the  $k$ -th video frame is carried

out by analyzing the set of admissible transmission strategies, each of which is characterized by its own delivery-time distribution. For each strategy, using the stochastic model, the corresponding distribution function of the delivery time of the video frame is determined, which makes it possible to quantitatively assess its suitability in terms of ensuring timely delivery.

The probability of delivering a video frame within the admissible deadline time for a given transmission strategy is defined as the value of the delivery-time distribution function at the point corresponding to the deadline:

$$\mathbb{P} \{T_k^{(s)} \leq T_d\} = F_{T_k^{(s)}}(T_d)$$

where  $F_{T_k^{(s)}}$  is the corresponding distribution function of the random variable of the delivery time of the video frame when using strategy  $s$ .

A graphical interpretation of a video frame as a controlled object with a delivery-time constraint is shown in Fig. 2.

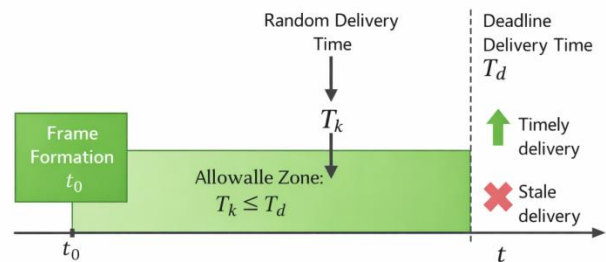


Fig. 2. Interpretation of a video frame as a controlled object with a delivery-time constraint

Source: compiled by the authors

The obtained value of the probability of timely delivery is used as a formalized criterion for evaluating the effectiveness of each transmission strategy. Thus, the process of making a control decision is reduced to comparing strategies by their ability to ensure delivery of a video frame within the specified time, taking into account the stochastic nature of the communication channel. Such a criterion directly corresponds to the requirements of real-time video services, for which decisive is not the very fact of frame delivery, but its timeliness.

It is important to note that the proposed formalization does not impose restrictions on the specific composition of the set of transmission strategies. The set of admissible strategies may change depending on the specifics of application, requirements for video quality, or operating conditions of the UAV network, without affecting the general structure of formalized control decisions. This ensures the universality of the approach and the possibility of adapting it to different usage scenarios

without modification of the mathematical basis of the method.

A change in the parameters of the communication channel or the structure of routes in the stochastic model is directly reflected in the form of the delivery-time distribution function and, accordingly, in the values of the probability of timely delivery for each strategy. Thus, the adaptability of the proposed transmission method is realized through a formalized relationship between the parameters of the stochastic model and the process of making control decisions, without using empirical or rigidly fixed rules.

It should be defined that the proposed method of video data transmission at the application layer in a UAV network is based on the following provisions.

1. The criterion for selecting a video frame transmission strategy is the maximization of the probability of its timely delivery within the specified deadline time.
2. The formalization of the method is carried out by using a stochastic model of the transmission process, which makes it possible, for each admissible strategy, to determine the delivery-time distribution and the corresponding probability of meeting the time constraints.
3. The rules for making control decisions consist in selecting the transmission strategy with the maximum probability of timely delivery and in discarding video frames that cannot be delivered within the admissible time.
4. The application of these provisions in combination ensures adaptive control of the video

data transmission process taking into account the stochastic nature of the communication channel.

Taking into account the presented formalization of control decisions, the proposed method of video data transmission can be generally presented in the form of the diagram in Fig. 3.

As can be seen from Fig. 3, the proposed method consists of several main components, namely principles (probabilistic timeliness), decision-making rules, a selection criterion, and formalization (a model, relationships). In addition, the formalization of control decisions based on a stochastic model creates a theoretical foundation for constructing an adaptive control algorithm for video frame transmission in a UAV network. The obtained relationships make it possible to move from a probabilistic description of the transmission process to an algorithmic implementation of the method of video data transmission.

The algorithm for video frame transmission with adaptive control implements the proposed method of video data transmission at the application layer by sequentially forming, evaluating, and transmitting each video frame, taking into account the stochastic characteristics of the delivery process. Unlike static transmission schemes, the algorithm envisages making control decisions for each video frame separately, which makes it possible to take into account the current state of the UAV network and ensure compliance with the time requirements for delivery.

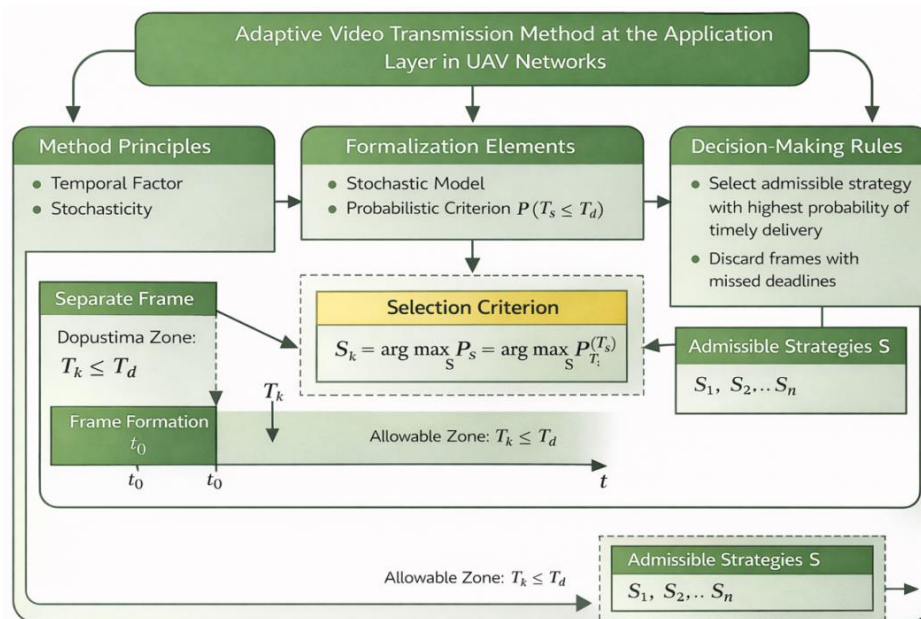
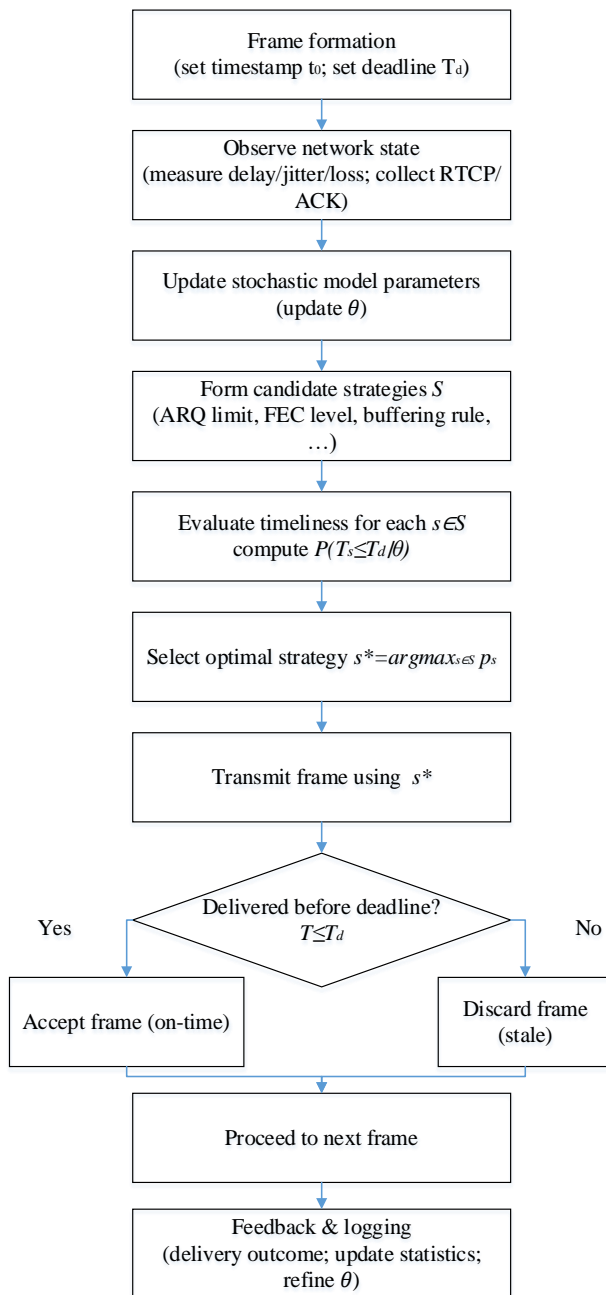


Fig. 3. General scheme of the method for video data transmission at the application layer

Source: compiled by the authors

The flowchart of the algorithm for video frame transmission with adaptive control in a UAV network is shown in Fig. 4.



**Fig. 4. Flowchart of the algorithm for video frame transmission with adaptive control in a UAV network**

Source: compiled by the authors

Let  $T_d$  denote the delivery deadline for a video frame, and let  $T_s$  be the random end-to-end delivery time under transmission strategy  $s \in S$ . The timeliness of strategy  $s$  is evaluated as  $p_s = P(T_s \leq T_d | \theta)$ , where  $\theta$  denotes the current parameter set of the stochastic delivery-time model estimated from network observations and feedback (e.g., delay,

jitter, and loss statistics). The selected strategy is  $s^* = \arg \max_{s \in S} p_s$ .

The algorithm begins with the formation of the next video frame on the unmanned aerial vehicle side. At the moment the frame is formed, the initial time is recorded, relative to which the admissible deadline delivery time is determined. In parallel, an assessment of the current state of the communication channel is performed, which is necessary to update the parameters of the stochastic model of the transmission process. Such an assessment may be based on the available information about delays, losses, or other quality-of-service indicators obtained during previous transmissions.

Based on the updated parameters of the stochastic model, for each admissible transmission strategy the distribution of the video frame delivery time is determined. Using the corresponding distribution functions, the algorithm computes the probability of delivering the frame within the specified deadline time for each strategy. The obtained probability values are used as a formalized basis for comparing transmission strategies and selecting the one that best meets the requirements for timely delivery of the video frame.

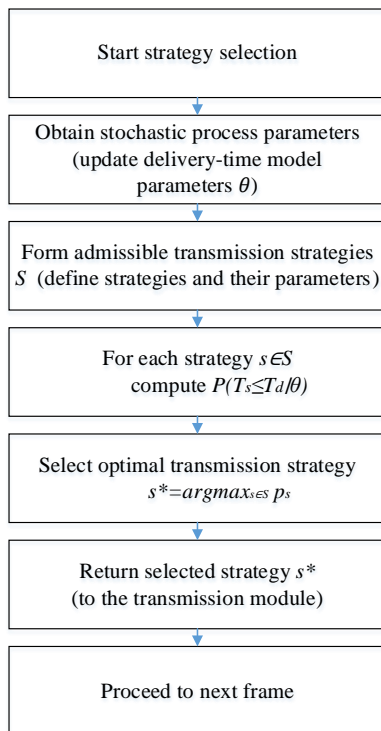
The flowchart of the algorithm for selecting video frame transmission strategies based on the probability of timely delivery is presented in Fig. 5.

After selecting the transmission strategy, the algorithm initiates the transmission of the video frame according to the selected parameters. During transmission, the frame delivery time is monitored with regard to the admissible deadline. If the video frame is delivered within the specified time, the frame is considered successfully transmitted and is processed by the receiving side. Otherwise, the frame loses relevance and may be discarded without performing additional actions, which corresponds to the requirements of real-time video services.

Adaptation of the transmission process is implemented by using the results of previous transmissions to update the parameters of the stochastic model. The actual delivery-time values and information about meeting or violating the time constraints are used as feedback to refine the characteristics of the transmission-process model. The updated model is applied when forming control decisions for subsequent video frames, which ensures adaptation of the algorithm to changing operating conditions of the UAV network.

The algorithm provides for cyclic repetition of the described stages for each subsequent video frame, which ensures continuous adaptation of the transmission process to changing operating conditions

of the UAV network. Owing to the use of a stochastic model of the transmission process, adaptation is carried out on the basis of predictive characteristics rather than exclusively on reactive mechanisms, which makes it possible to reduce the number of overdue frames and avoid the accumulation of delays.



**Fig. 5. Flowchart of the algorithm for selecting video frame transmission strategies based on the probability of timely delivery**

Source: compiled by the authors

An important property of the proposed algorithm is its independence from specific implementations of transport or network protocols. The algorithm operates at the application layer and uses only the information available at this layer, which ensures the possibility of its implementation on top of existing video data transmission protocols without the need to modify them. This makes the algorithm suitable for practical use in real UAV systems with different hardware and software platforms.

Thus, the proposed algorithm for video frame transmission with adaptive control implements the method of video data transmission at the application layer by combining stochastic prediction of delivery time with a formalized selection of the transmission strategy. The algorithmic implementation provides a basis for further experimental study of the method's effectiveness and for assessing its impact on the probability of timely delivery of video data in a UAV network.

## INTEGRATION OF THE VIDEO DATA TRANSMISSION METHOD AT THE APPLICATION LAYER WITH APPLICATION-LAYER VIDEO TRANSMISSION PROTOCOLS

The video data transmission method does not provide for changes in the structure of application-layer video transmission protocols; however, it requires determining a way of functionally aligning its elements with the existing mechanisms of these protocols. Such alignment consists in mapping the abstract components of the method specifically the video frame deadline, the transmission strategy, and feedback onto parameters and procedures that are already implemented at the application layer.

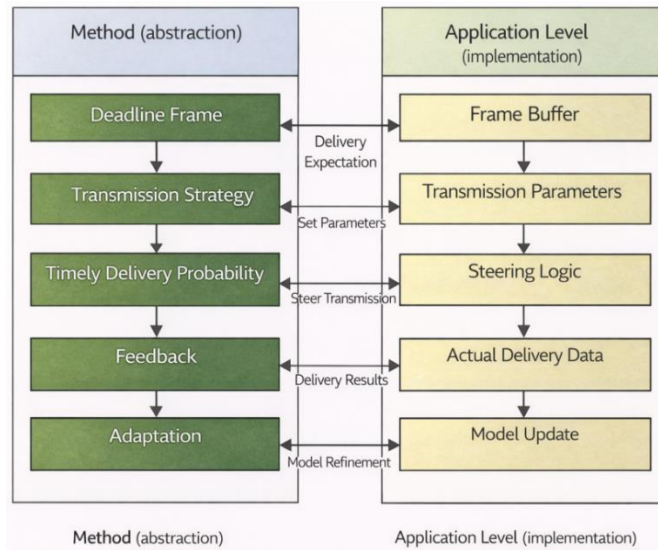
The functional mapping of the main elements of the proposed method onto application-layer mechanisms is shown in Fig. 6.

The video frame deadline, which is used in the method as a key parameter for making control decisions, does not require explicit representation in the protocol format. It is used exclusively at the application layer as an internal time limiter that determines the admissibility of delivering a specific video frame. Thus, the method does not impose requirements for deadline support in the protocol, but applies deadlines as a logical attribute of the video data.

The transmission strategy, selected according to the proposed criterion, determines the way in which the mechanisms of the application protocol are used, in particular the parameters of video frame segmentation, the order of transmission, and the admissibility of retransmission. At the same time, the method does not change the protocol mechanisms themselves, but only controls their use within the existing functionality, which makes it possible to regard it as an external mechanism for controlling the transmission process.

The feedback required for adaptive control is formed on the basis of information available at the application layer after the completion of video frame transmission. Such information includes the actual frame delivery time or the fact of violating the time constraints. The obtained data are used to refine the parameters of the stochastic model of the transmission process and do not require specialized extensions of application protocols.

The place of the proposed method in the overall chain of application-level video transmission in a UAV network is illustrated in Fig. 7.



**Fig. 6. Functional mapping of the method elements onto the application layer**  
Source: compiled by the authors

**Adaptation of the use of RTP/RTCP protocols to the conditions of UAV networks.** The use of RTP/RTCP protocols in unmanned aerial vehicle networks is accompanied by a number of specific limitations caused by high topology dynamics, communication channel instability, significant delay variability, and the limited validity time of video information. Under such conditions, the standard RTP/RTCP mechanisms, oriented mainly toward delivering the full video stream and evaluating average transmission quality indicators, do not always meet the requirements of UAV video surveillance, navigation, and situational awareness tasks.

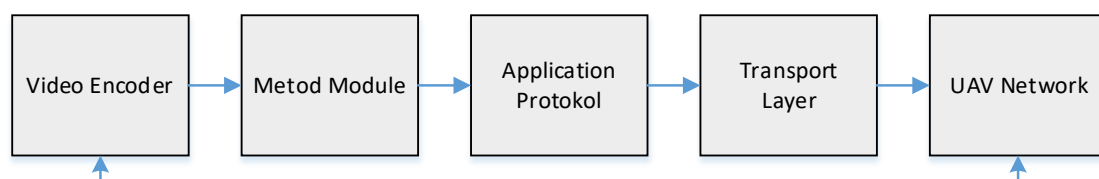
The differences between the standard use of RTP/RTCP protocols and their adapted application in UAV networks are shown in Fig. 8.

In the standard RTP/RTCP usage scenario (left part of Fig. 8), the video data transmission process is focused on continuous sending of RTP packets, and RTCP feedback is used mainly to evaluate packet loss, jitter, and average delay. Decision-making on transmission parameters is reactive in nature and aimed at improving the statistical characteristics of the stream as a whole, without taking into account the temporal value of individual video frames.

Under such conditions, retransmission of packets is considered expedient even in cases when a video frame loses relevance for the application task.

In contrast, the proposed method changes the logic of using RTP/RTCP taking into account the specifics of UAV networks (right part of Fig. 8). The central element of the adaptation is the introduction of a video frame deadline as an internal application parameter that determines the admissibility of its delivery. In this case, RTP is used exclusively as a mechanism for transporting video data, while decisions about the expediency of transmitting or retransmitting a frame are made at the application layer, taking into account the probability of timely delivery.

The feedback formed using RTCP in the proposed method is interpreted not as an indicator of average stream quality, but as a source of information for refining the stochastic model of the video frame delivery process. Even under the condition of delayed or aggregated RTCP reports, which is typical for UAV networks, the method provides predictive decision-making by estimating the probability of meeting the deadline for subsequent frames.



**Fig. 7. Application-layer video transmission pipeline with the proposed method module in a UAV network**  
Source: compiled by the authors

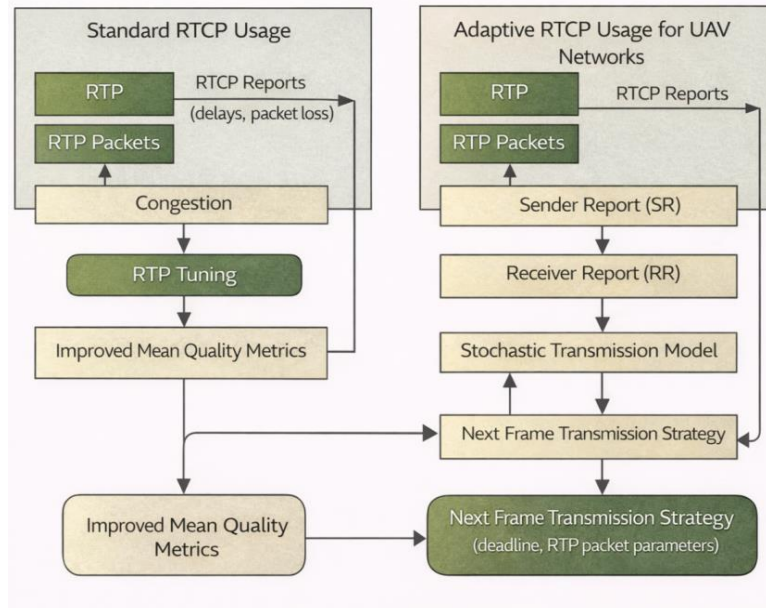


Fig. 8. Comparison of standard and adapted use of RTP/RTCP protocols in UAV networks

Source: compiled by the authors

Thus, the transition from reactive control oriented toward statistical stream indicators to deadline-oriented adaptive control makes it possible to take into account the specifics of UAV networks, where the key factor is not the completeness of the video stream, but the timeliness of receiving information.

**Limitations and application scenarios of the method in UAV networks.** The proposed method of video data transmission at the application layer is oriented toward use in UAV networks; however, its effectiveness and advisability of application are determined by a number of conditions and limitations related both to the characteristics of the network environment and to the specifics of application tasks. Awareness of these limitations is necessary for correct interpretation of the results and for determining scenarios in which the method provides the greatest practical effect.

One of the key limitations of the method is the assumption of the possibility of estimating the statistical characteristics of the video frame delivery process. The method is based on the use of a stochastic model whose parameters are refined based on feedback. In cases where feedback is excessively limited or completely absent for a long time, the accuracy of estimating the probability of timely delivery may decrease, which affects the quality of control decisions.

Another limitation is the computational complexity associated with forming the set of transmission strategies and estimating the corresponding probabilities. Although the proposed method does not require complex optimization

procedures, its application assumes the availability of sufficient computational resources on board the UAV or at the ground control station. In scenarios with strict hardware constraints, the set of admissible strategies may be reduced, which decreases the adaptivity of the method.

The method is also oriented toward scenarios in which the key quality criterion is the timeliness of receiving video information, rather than the completeness of the video stream. In applications where significant delays are permissible or where video is used for archiving, the proposed approach may have no advantages over traditional transmission methods oriented toward loss minimization.

The most appropriate application scenarios of the method are real-time video surveillance tasks, navigation support, search and rescue operations, and situational awareness, in which the relevance of video frames rapidly decreases over time. Under such conditions, the use of a deadline-oriented approach makes it possible to concentrate network resources on transmitting video information that has the greatest practical value.

## EXPERIMENTAL SETUP AND EVALUATION METRICS

The purpose of the experimental study is to quantitatively evaluate the effectiveness of the proposed method of video data transmission at the application layer in UAV networks under conditions that reflect the characteristic features of the operation of such networks. The experiments are aimed at verifying the ability of the method to ensure timely

delivery of video frames in the presence of variable delays, an unstable communication channel, and a limited relevance time of video information.

The experimental setup involves modeling the process of transmitting a sequence of video frames from the UAV to the receiving side, taking into account the stochastic nature of delivery delays. Each video frame is characterized by the moment of formation and a specified deadline that determines the maximum allowable delivery time. During the experiment, the actual delivery time of frames is recorded, on the basis of which a decision is made about their timeliness or loss of relevance.

The deadline  $T_d$  is interpreted as the relevance time of a video frame for the application task and is set proportionally to the frame period  $T_f = 1/f$ . The studies consider the range  $T_d \in [2T_f, 4T_f]$  for observation tasks and  $T_d \in [T_f, 2T_f]$  for navigation control tasks.

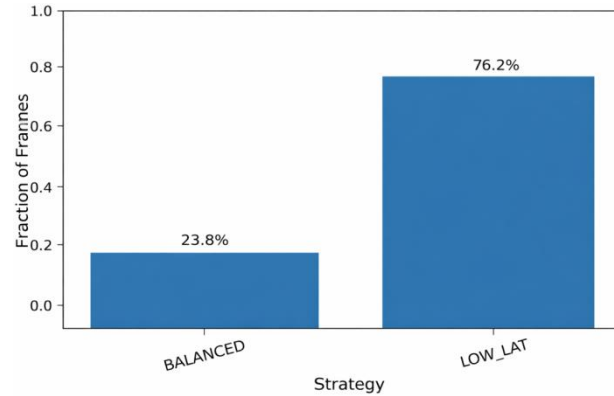
To evaluate the effectiveness of the proposed method, a system of metrics focused on the temporal characteristics of video data transmission is used. The main metric is the probability of timely delivery of a video frame, which is defined as the fraction of frames delivered within the specified deadline out of the total number of transmitted frames. This metric directly reflects the ability of the method to take into account the temporal value of video information, which is critically important for UAV networks.

Additionally, the average actual delivery time of video frames is analyzed, which makes it possible to assess the impact of adaptive control on transmission delays. Although this metric is not decisive for evaluating video relevance, it is used for comparison with baseline approaches and for interpreting the obtained results.

Another auxiliary metric is the fraction of video frames discarded due to missing the deadline. This indicator makes it possible to evaluate the efficiency of network resource usage and the degree of concentration of transmission on relevant video information. Reducing the number of stale frames arriving at the receiver is considered a positive effect of applying the proposed method.

To ensure correctness of comparison, the experimental results are analyzed relative to a baseline approach to video data transmission in which there is no mechanism of deadline-oriented adaptive control. This approach makes it possible to quantitatively assess the contribution of the proposed method to improving the timeliness indicators of video frame delivery.

Fig. 9 shows the distribution of the choice of video frame transmission strategies formed by the proposed adaptive method during the experiment.



**Fig. 9. Distribution of video frame transmission strategy selection by the adaptive method**

*Source: compiled by the authors*

Fig. 9 shows the distribution of the selection of video frame transmission strategies formed by the proposed adaptive method during experimental simulation for a sequence of 800 video frames.

As can be seen from Fig. 9, the dominant strategy in the considered scenario is the LOW\_LAT strategy, which was selected for approximately 76.2% of the video frames. The BALANCED strategy was applied in 23.8 % of cases. The ROBUST strategy was not selected in this experiment, which indicates the absence of conditions under which its use would provide an advantage according to the chosen optimality criterion.

The obtained distribution of strategy selection reflects the operating nature of the adaptive method, which is oriented toward maximizing the probability of timely delivery of video frames for a given deadline. The predominant selection of the LOW\_LAT strategy indicates that, at most points in time, the current state of the communication channel allowed reducing the average delivery time without a significant increase in the risk of frame loss. At the same time, the non-zero share of selecting the BALANCED strategy indicates that the adaptation algorithm responds to deterioration of channel parameters and switches to a more conservative transmission strategy.

Thus, the results presented in Fig. 9 confirm that the proposed method does not use a fixed transmission strategy, but performs a dynamic choice among alternatives according to the current network state and the time requirements for video frame delivery.

To clarify the adaptation mechanism, it is advisable to consider how the selected strategy changes over time and how these changes are consistent with transitions of the communication channel between modes with favorable and deteriorated characteristics.

Fig. 10 shows the time sequence of selecting the video frame transmission strategy with highlighting of bad-mode intervals.

Fig. 10 shows the time trajectory of the selection of the video frame transmission strategy by the proposed adaptive method during experimental simulation. The x-axis shows the video frame number (a time axis in discrete representation), and the y-axis shows the selected transmission strategy from the set of available strategies (LOW\_LAT, BALANCED, ROBUST). Light vertical shading marks the intervals in which the communication channel is in a state of degraded characteristics (bad mode), which corresponds to an increase in delivery delays and/or the probability of losses in the channel model.

The figure demonstrates that the adaptive algorithm performs dynamic switching between strategies depending on the current channel state. In intervals where the bad-mode shading is absent, the LOW\_LAT strategy is predominantly used, oriented toward minimizing delivery delay. In contrast, during periods of channel degradation (shaded regions), the algorithm more often switches to the BALANCED strategy, which provides a more conservative use of network mechanisms and increases the probability of timely delivery under increased stochastic uncertainty.

Importantly, strategy switching is not instantaneous and may occur with a delay relative to the beginning of a bad interval. This is explained by the feedback mechanism, which in the implemented testbed is periodic and arrives with a lag (an RTCP-like scheme). Therefore, the adaptation method operates on the basis of updating the parameters of the stochastic model using the results of previous transmissions, which is realistic for UAV networks, where information about the channel state is available with delays and may be incomplete.

Thus, Fig. 10 clearly confirms the presence of an adaptive control mechanism. The choice of the

transmission strategy correlates with changes in the channel state and changes over time according to the received feedback and the estimated parameters of the delivery model.

For a quantitative assessment of the effectiveness of the proposed method, it is advisable to consider a comparison of the probabilistic characteristics of video frame delivery for the adaptive and baseline approaches.

Fig. 11 presents a comparison of key probabilistic performance metrics for the ADAPTIVE and BASELINE approaches [20].

The baseline approach (BASELINE) within the experiment implements video frame transmission with a fixed strategy without taking into account the deadline and without adaptive change of transmission parameters depending on the channel state.

In Fig. 11, the first metric,  $P_{\text{timely}}$ , reflects the probability of timely delivery of a video frame, i.e., the fraction of frames delivered within the specified deadline. From Fig. 11 it can be seen that the adaptive method demonstrates higher values of this metric compared to the baseline approach. In the conducted experiment ( $N=800$  frames), the following numerical estimates were obtained: for ADAPTIVE,  $P_{\text{timely}}=0.77875$ ; for BASELINE, respectively,  $P_{\text{timely}}=0.72125$ . This indicates the effectiveness of the strategy selection mechanism oriented toward the temporal relevance of video data and confirms the ability of the method to increase the probability of receiving information useful for the application task.

The second metric, the loss probability, characterizes the fraction of video frames that were not delivered to the receiving side due to losses in the communication channel. For the adaptive method, a somewhat higher level of losses is observed compared to the baseline approach.

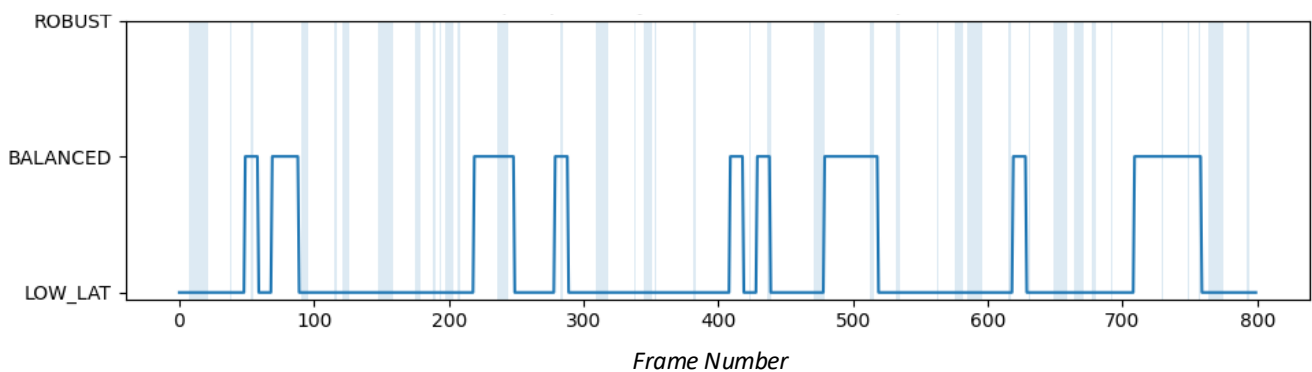
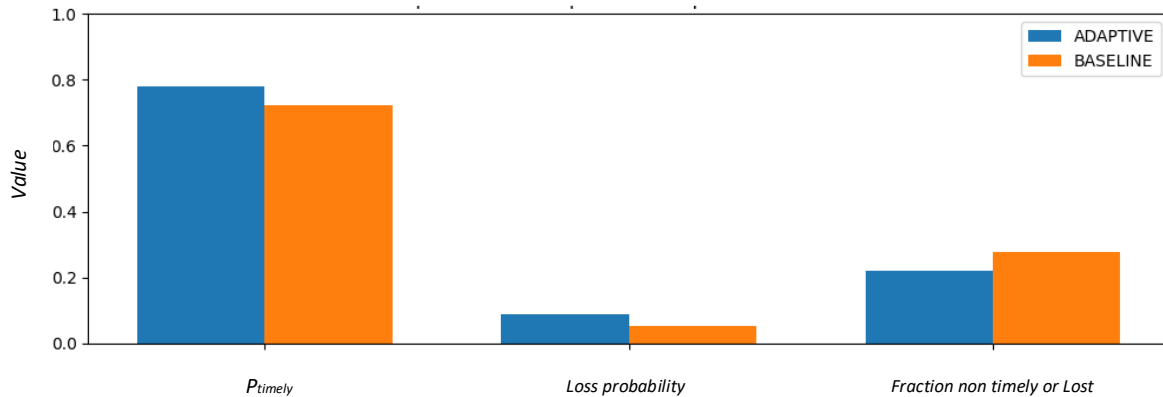


Fig. 10. Transmission strategy selection over time

Source: compiled by the authors



**Fig. 11. Histograms comparing probabilistic and fractional performance metrics of video frame transmission for the proposed adaptive method (ADAPTIVE) and the baseline approach without deadline-oriented control (BASELINE)**

Source: compiled by the authors

The loss probability for ADAPTIVE is  $P_{loss}=0.08875$ , and for BASELINE  $P_{loss}=0.05375$ . This result is expected and is explained by the fact that optimization with respect to the timeliness criterion assumes the possibility of using lower-latency strategies that admit an increased risk of frame loss. In this case, the increase in loss probability is considered a controlled trade-off within the proposed method.

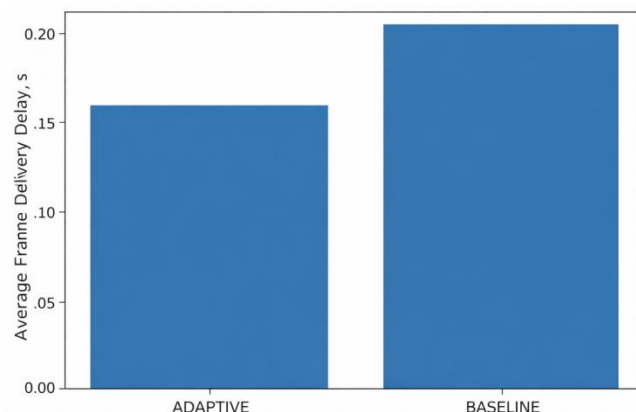
The third metric, the fraction of non-timely or lost frames, integrates the impact of both deadline violations and actual delivery losses. From Fig. 11 it can be seen that the adaptive method reduces this fraction compared to the baseline approach (fraction of non-timely or lost frames for ADAPTIVE = 0.22125, fraction of non-timely or lost frames for BASELINE = 0.27875). This means that the overall number of video frames that cannot be used as intended due to lateness or loss decreases, despite a slight increase in the loss probability.

Let us consider the temporal characteristics of video frame delivery.

Fig. 12 presents a comparison of the average delivery delay of video frames for the proposed adaptive video data transmission method (ADAPTIVE) and the baseline approach without deadline-oriented control (BASELINE).

From Fig. 12 it can be seen that the use of the adaptive method provides a smaller average delivery delay compared to the baseline approach. This means that the increase in the probability of timely delivery, shown in Fig. 11, is achieved not by increasing transmission latency, but due to a more efficient selection of the transmission strategy in accordance with the current state of the communication channel and the time constraints.

The obtained result confirms that the proposed method not only increases the temporal relevance of video frames, but also contributes to reducing the typical delivery delays for those frames that are successfully received by the receiver. Thus, adaptive control does not lead to degradation of the temporal characteristics of transmission; on the contrary, it ensures more prompt delivery of video information.



**Fig. 12. Histograms comparing the average delivery delay of video frames for the proposed adaptive video data transmission method (ADAPTIVE) and the baseline approach without deadline-oriented control (BASELINE)**

Source: compiled by the authors

Together with the results presented in Fig. 11, Fig. 12 demonstrates a comprehensive positive effect of the proposed method: a decrease in the fraction of irrelevant video frames is accompanied by a decrease in the average delivery delay, which is especially important for application tasks in UAV networks with strict time constraints.

Thus, Fig. 9, Fig. 10, Fig. 11 and Fig. 12 summarize the effect of applying the proposed method at the level of integral indicators. Compared

to the baseline approach, the proposed method increases  $P_{\text{timely}}$  by 0.0575 and reduces the average delay of delivered frames by 0.0528 ( $\approx 52.8$  ms). The fraction of non-timely or lost frames decreases by 0.0575. This proves that adaptive control increases the probability of timely delivery and reduces the fraction of frames that lose relevance, with an acceptable trade-off in terms of loss probability.

To assess the impact of the strictness of time constraints on the effectiveness of the proposed method, let us consider the dependence of the probability of timely delivery of video frames on the deadline value.

Fig. 13 shows the dependence of the probability of timely delivery of video frames on the deadline value  $T_d$  for the proposed adaptive method (ADAPTIVE) and the baseline approach without deadline-oriented control (BASELINE).

From Fig. 13 it can be seen that under strict time constraints (small values of  $T_d$ ) the adaptive method significantly outperforms the baseline approach in terms of timeliness of delivery. In particular, at the minimum deadline values the difference between the ADAPTIVE and BASELINE curves is the largest, which indicates the effectiveness of the adaptive strategy selection mechanism precisely under conditions of limited time available for delivering video information.

As the deadline gradually increases the probability of timely delivery increases for both approaches, and the difference between them decreases. For sufficiently large values of  $T_d$ , the curves approach each other, which means that the role of adaptive control decreases under weak time constraints. Such behavior is expected and confirms the correct operation of the proposed method without artificially inflating the effect.

The obtained dependence demonstrates that the main advantage of the adaptive method manifests itself precisely in the regimes that are most characteristic of UAV networks, namely when there is a need for prompt delivery of video data with strict requirements for information relevance. Thus, Fig. 13 summarizes the experimental results and confirms the expediency of using deadline-oriented adaptive control in application tasks of video transmission in UAV networks.

Thus, the results presented in Fig. 9, Fig. 10, Fig. 11, Fig. 12 and Fig. 13 confirm that the proposed method of video data transmission makes it possible to increase the time efficiency of video information delivery and reduce the fraction of irrelevant frames due to a controlled trade-off between latency and transmission reliability. The selected evaluation metrics make it possible to comprehensively analyze the behavior of the proposed method in a dynamic network environment and to draw objective conclusions about its effectiveness under conditions typical for UAV networks.

## CONCLUSIONS

The concept of adaptive control of the video frame transmission process is formulated as predictive decision-making based on the stochastic characteristics of delivery time, where the key objective is not minimizing the average delay, but ensuring probabilistic timeliness of delivery.

A method of video data transmission at the application layer with adaptive control in a UAV network is developed, which consists of a stochastic model for determining the random variable of the video frame delivery time, a general algorithm for frame transmission with deadline control, and an algorithm for selecting a strategy based on the probability of timely delivery using feedback to update the model parameters.

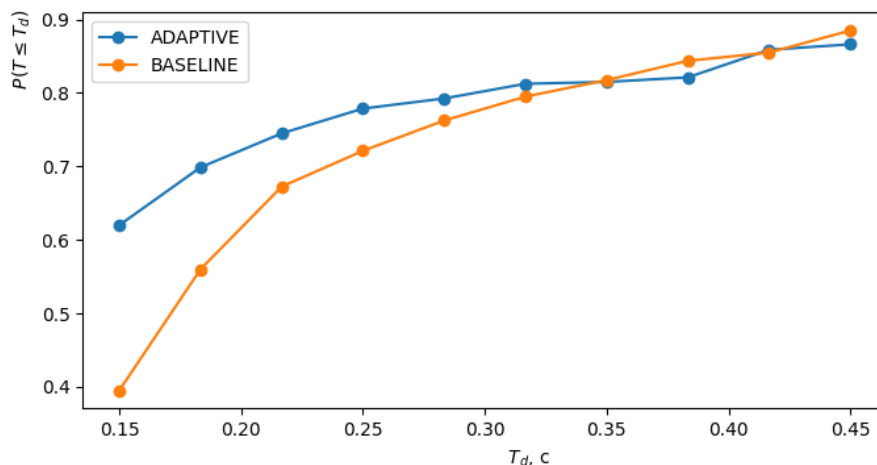


Fig. 13. Plots of the dependence of the probability of timely delivery on the deadline

Source: compiled by the authors

The possibility of integrating the method with application-layer video transmission protocols without modifying their structure is shown. The deadline is used as an internal application attribute, the strategy as a way of controlling the use of available mechanisms (segmentation, transmission order, retransmissions), and feedback as a source of data for refining the stochastic model.

Limitations and the most appropriate scenarios for applying the method in UAV networks are identified. The method is most effective in real-time tasks with strict time requirements (surveillance, navigation control, situational awareness), provided that at least minimal feedback is available and sufficient computational resources are present.

Experimental simulation confirmed the effectiveness of the proposed approach. For  $N=800$

frames, the adaptive method provided a higher probability of timely delivery  $P_{\text{timely}}=0.77875$  versus 0.72125 for BASELINE (increase of +0.0575), a smaller average delay of delivered frames 0.1629 s versus 0.2157 s (decrease of  $\approx 0.0528$  s), and a smaller fraction of non-timely or lost frames 0.22125 versus 0.27875 (decrease of  $-0.0575$ ), with a controlled trade-off in loss probability.

The study of the dependence of timeliness on the deadline showed that the advantages of the method are most pronounced under strict time constraints typical for UAV networks, and as the deadline increases, the difference with BASELINE decreases, which confirms the correctness of the adaptive logic without an “artificial” effect.

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## **Метод передачі відеоданих на рівні застосунків з адаптивним керуванням у мережі безпілотних літальних апаратів**

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## АНОТАЦІЯ

Відеопотоки, що передаються з безпілотних літальних апаратів (БПЛА), є критичним джерелом ситуаційної інформації для моніторингу, пошуково-рятувальних робіт, реагування на надзвичайні ситуації та завдань безпеки. У таких часово-критичних сценаріях практична цінність відеокадру швидко зменшується після настання дедлайну, тоді як мережі безпілотних літальних апаратів характеризуються стохастичною мінливістю затримок, джитеру, втрат і динамічною топологією. Тому актуальною є задача забезпечення своєчасної доставки відеокадрів за рахунок адаптивного керування на рівні застосунків. **Об'єктом дослідження** є процес передавання відеокадрів у мережах безпілотних літальних апаратів за стохастичних умов каналу та маршрутизації. **Предметом дослідження** є методи та моделі адаптивного керування доставкою відеокадрів на рівні застосунків, зокрема вибір стратегії за наявності обмежень за дедлайном. **Метою роботи** є розроблення методу адаптивного передавання відеокадрів на рівні застосунків, який підвищує ймовірність доставки до дедлайну та зменшує частку кадрів, доставлених із запізненням або втрачених, у мережах безпілотних літальних апаратів. **Результати дослідження.** Запропоновано концептуальну основу адаптивного керування передаванням відеокадрів, що включає модель прийняття рішень для вибору стратегій передавання на підставі спостережуваних мережових умов і вимог щодо дедлайну. Розроблено адаптивний алгоритм вибору стратегії для кожного кадру, який враховує правила обмеження повторних передавань, керування буферизацією та механізми робастності (наприклад, доставку на основі надмірності). Визначено набір метрик оцінювання своєчасності та надійності, зокрема ймовірність своєчасної доставки, середню затримку доставлених кадрів, ймовірність втрати та частку кадрів, доставлених із запізненням або втрачених. Моделювання показує, що адаптивне керування підвищує дедлайнову надійність порівняно з фіксованими стратегіями передавання в репрезентативних режимах мереж безпілотних літальних апаратів.

**Ключові слова:** мережі безпілотних літальних апаратів; відеостримінг; керування на рівні застосунків; адаптивне передавання; дедлайнова надійність; стохастична затримка; джитер; втрата пакетів

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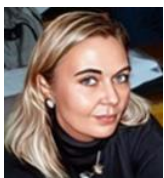


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