AUTOMATION AND COMPUTER-INTEGRATED TECHNOLOGIES

UDC 629.735.2:681.324(045)
DOI:10.18372/1990-5548.85.20430

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DECENTRALIZED LOCAL-PRIORITY COMMUNICATION PROTOCOL FOR SMALL UNMANNED AERIAL VEHICLE SWARMS

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Abstract—*The paper proposes a decentralized communication protocol for small swarms of unmanned aerial vehicles that provides prioritized access to the control channel with limited radio resources. The approach is based on local priority selection, agent slot mapping with seat rotation for long-term fairness, and probabilistic sparsity within. This combination manages the load in a mathematical expectation, reduces the probability of collisions, and ensures low latency delivery of priority control messages without a central dispatcher. The simulation results for a swarm of 12 unmanned aerial vehicles demonstrate an increase in usable throughput, median delay at the level of one epoch, and collision rate at the level of the baseline approach with a significantly higher number of successful transmissions.*

Keywords—Unmanned aerial vehicle swarms; decentralized communication protocol; medium access control; local-priority access; probabilistic thinning; token-bucket control; distributed max-consensus; neighborhood selection; event-triggered coordination; multi-hop flying ad hoc networks; low-latency control messaging.

I. INTRODUCTION

Swarms of unmanned aerial vehicles (UAVs) in the tactical range of 5–15 units are increasingly being used to intercept air targets, conduct multi-sensor surveillance, and operate in environments with a risk of electronic interference. Their key advantages – scalability, functional redundancy, survivability, ability to perform subtasks in parallel and rapid reconfiguration of formations – are confirmed by modern reviews of swarm systems and network technologies for UAVs [15], [16], [22]. Due to cooperation, swarms achieve a better cost-effectiveness ratio than equivalent single platforms, especially against numerous or maneuverable air threats [16], [22].

At the same time, in real-world conditions, swarm interaction imposes severe technological limitations: multi-hop wireless networks (FANETs) have variable bandwidth and latency, are subject to interference and losses, and navigation subsystems often operate in GNSS-denied environments [8], [9], [15]. Studies show that even with the use of advanced routing and Medium Access Control (MAC) methods, the swarm throughput is likely to be limited, and access queues degrade rapidly during peak loads when multiple devices simultaneously initiate the exchange of control messages [9], [10], [11], [12], [18]. From the side of control algorithms, it is known that event-triggered schemes reduce the amount of traffic for, but do not by themselves resolve the radio channel access conflict and do not guarantee minimum latency for priority control messages [1] – [6].

Therefore, in order for the swarm to be effective, each UAV must have a formalized local algorithm of actions with respect to the task and the current state of the network: when to initiate the transmission of the control message, the right time from the available channel resource, how to limit the transmission frequency, and how to ensure priority for the most important information packets without a centralized dispatcher [9], [10], [18]. Such an algorithmic layer should decentralize important messages, limit the total load during peak loads, ensure low delivery latency for critical updates, and maintain fair access distribution between devices in the long run [9], [10], [15], [18], [22]. Additionally, it should be compatible with a typical swarm hardware set, which includes: a multi-channel wireless subsystem (high-speed 802. 11s/5G sidelink for operational exchange, a backup low-speed long-range channel – LoRa/FSK – for service messages, UWB transceivers for mutual range measurements and relative localization); time synchronization means (PTP/IEEE 1588 or "air" reference beacon; if available – GNSS/GPSDO); on-board computing

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platform (autopilot and computing module under RTOS/ROS 2) with support for the network stack (mesh routing, access control to the environment); navigation and sensor complex (INS: IMU + barosensor + magnetometer, altimeter, UWB; if necessary, a camera/lidar/radar for environmental assessment); and security features (authentication and integrity of control messages at the packet level using the AEAD scheme, key management, anti-repetition protection). This configuration ensures the allocation of M control slots per epoch, stable synchronization, and robust interaction in the face of loss and interference [13], [14], [22].

II. Literature Review

Each device is equipped with a lightweight computing stack: an industrial-grade autopilot (PX4/ArduPilot) paired with a Linux RT/ROS 2 processor module or RTOS controller, which guarantees the performance of local priority estimates and short exchanges in real time; the experience of deploying such stacks for swarm scenarios is given in current reviews and applied works [9], [15], [19]. The sensor subsystem includes INS (IMU+barometer), altimeter, and, if available, GNSS; to support relative navigation and increase stability in GNSS-denied, the basic sensors include UWB rangefinders (two-way time of flight) with integration into local state filters - these measurements are used to form the priority components (measurement innovation and proximity indicators to relevant objects) and to maintain network synchronization coherence [13], [14], [15]. To reduce vulnerability and ensure reproducibility, control messages and access metadata (slot ID, local rank in the token-bucket state) are logged on the onboard media with periodic aggregation at the ground station; the ground segment performs the functions of monitoring/analysis and the initial mission task, but the algorithm remains fully decentralized and operable without it [9], [15]. With regard to the security of swarm networks, authentication and integrity are used for short frame-level control messages (AEADs) with low computational overhead and replay protection; current reviews on the security of swarm networks confirm the need for such mechanisms even in local control exchanges [22]. In the end, the combination of these tools – multiradio with dedicated slots per epoch, synchronized time base, UWB for relative navigation, lightweight onboard computing platform, and basic cryptographic protection - creates a minimum sufficient technical environment for the algorithm to work correctly in a swarm and reproducibly evaluate its performance (collision rate, control channel bandwidth, priority message latency, access fairness) in realistic scenarios To implement the proposed decentralized swarm interaction protocol, the following set of technical means was adopted, in compliance with the requirements of decentralization: the absence of a central dispatcher and arbitrator nodes in the decision-making cycle; decision-making and calculation of priorities on board each UAV only based on local information and exchanges in the vicinity of the vertex of the radius K synchronization of slots according to a distributed procedure (PTP/air beacon) without dependence on the base station; preservation of operability in case of loss of any individual node; autonomous limitation of the transmission frequency (token-bucket) without centralized quotas; decentralized authentication of control messages and key management. At the communication level, a multi-hop aviation ad hoc network (FANET) is used, i.e. a network in which packets are transmitted between UAVs through one or more intermediate repeater nodes (without fixed infrastructure; topology is variable, routes are dynamically rebuilt). The network is suitable for operation in variable channel conditions and during peak loads; practical prerequisites and limitations for such networks are described in detail in modern works on multihop access and MAC/routing protocols for UAVs. [9] – [12], [15], [18]. Physical access is realized as multi-radio: one interface for high-speed exchange (802.11s/802. 11ac in ad hoc mode or 5G sidelink), one for long-distance backup low-speed messages (LoRa/SigFox), and UWB transceivers for mutual distance measurements and (if necessary) epoch synchronization; this combination proves to increase the reliability of swarm interaction in the face of bandwidth fluctuations and packet loss: the high-speed channel is used for operational exchange, and the backup low-speed channel is used for service and emergency messages. UWB (Ultra-Wideband) provides mutual range measurements between UAVs and time synchronization, which gives stable relative localization and fast initial binding even in GNSS-denied conditions (in the absence of satellite navigation) [8], [9], [13], [14], [18]. The time base is formed through a common reference clock – a time agreed upon between all UAVs, synchronized, for example, according to the Precision Time Protocol (IEEE 1588). If no infrastructure is available, an "air beacon" is used – a short periodic timestamped message that is broadcast by swarm nodes in turn to align their clocks; this allows each epoch to be divided into discrete slots of equal duration for all

UAVs. Consistent slots are needed for two operations: selecting transmitters according to local priority and binding selected nodes to specific slots, without a central controller [9] – [14], [18], [22].

III. PROBLEM STATEMENT

Swarms UAVs operate in multi-hop wireless networks (MWNs) with time-sharing and limited channel resources. Even with modern routing/MAC protocols and event-activated consensus control schemes, a basic contradiction remains unresolved: when many agents simultaneously initiate the transmission of important control messages, the shared access medium is overloaded, leading to collisions and increased delivery delays [1] – [6], [9] – [12], [18], [22]. To maintain swarm efficiency in such modes, each UAV must implement a local decision-making algorithm for initiating transmission, selecting a slot, and adjusting its own intensity, which in a decentralized way prioritizes important messages, limits the load, and guarantees low delays [9], [10], [15], [18], [22].

The UAV radio interface is a shared half-duplex medium: at one point in time, a node either transmits or receives. Let the length of the control message be

Consider a swarm of $N \in [5,15]$ UAVs communicating via a multi-hop wireless network $G = (V, \varepsilon)$ The hour is discretized by epochs. $t \in \mathbb{N}$ with the period T_s; within each epoch, a limited management resource is available in the form of $M \in \mathbb{N}$ discrete slots, where $M \le M_{\max} = \lfloor (Ts - T_{sync}) / T_{tx} \rfloor$ is determined by the airtime of the package T_{tx} official invoices for short control messages. Each UA $i \in V$ locally evaluates scalar priority

$$s_i(t) = \alpha I_i(t) + \beta D_i(t) + \lambda A_i(t),$$
$$s_i(t) = \alpha I_i(t) + \beta D_i(t) + \lambda A_i(t),$$

where K is the normalized measurement innovation in its state filter; $D_i(t) \in [0,1]$ is a normalized measure of proximity to a relevant object/event (e.g., a target); $A_i(t) \in [0,1]$ is the normalized "age" from the last successful transmission. The goal is to ensure that the most important messages arrive with minimal delay and that the total channel load remains manageable even during peak loads [9], [10], [18], while basic event-based schemes without access control do not guarantee this [1] – [6].

Let N_i – set of immediate neighbors i, and $N_i^{(K)} = \{ j \in V \mid d_G(i,j) \le K \}$ nodes at the shortest distance no more than K ribs. Apparatus i is considered a local "candidate for transfer" in the era t, if it is a strict maximum K

$$s_i(t) > s_j(t), \ \forall j \in N_i^{(K)} \setminus \{i\}.$$

Such a choice reduces the number of simultaneous applicants without global coordination (local "filtering" by priority), which is a necessary step in a limited M [9], [18].

The mapping of candidates for slots is performed in a decentralized manner through "regionalization": each agent is assigned a region (and, accordingly, a slot) by deterministic mapping

$$r(i,t) = (hash(i, \phi(t)) \bmod M),$$
$$r(i,t) \in \{0,1,\ldots,M-1\},$$

where $\phi(t)$ is a common swarm sid of the era (variable over time for long-term fairness). Thus, competition for access occurs only between candidates from the same region. We denote by $C(t) \subseteq V$ is the set of all candidates according to the maximum rule, and through $C_r(t) = \{ i \in C(t) \mid r(i,t) = r \}$ candidates in the region r.

For load control in each region, probabilistic "dilution" is applied: each $i \in C_r(t)$ initiates a transmission attempt with probability

$$p_r(t) = \min\left(1, \frac{c}{\max(1, |C_r(t)|)}\right), \ c \in (0, \infty),$$

and the final decision is limited to the tokenized blockchain. Thus, even with a large number of local candidates in a region, the expected number of attempts in that region does not exceed a constant, and short-term "explosions" of activity of a single node are smoothed out [9], [10], [18].

The analytical motivation for this combination of rules lies in three properties. First, the load constraint in the mathematical expectation: if $T_r(t)$ – number of attempts in the region in an epoch t provided that $|C_r(t)| = C \ge 1$ have $T_r \sim Bin(C, c/C)$ and, therefore, $\mathbb{E}[T_r] = c$, then $C = 0$, then $E[Tr] = 0$. Hence $E\left[\sum_{r=0}^{M-1} T_r\right] \le Mc$ and, picking $c \le 1$ we get

$$E\left[\sum_{i \in V} a_i(t)\right] \le M$$

that is, the expected total load on the control channel in each epoch does not exceed the number of available slots. This is exactly the resource constraint that "pure" event-based schemes do not adhere to during peak loads [1] – [6], [9], [10], [18]. Second, the upper bound on the collision frequency in each region follows from the distribution of T_r. The probability of a collision in the region is $\mathbb{P}\{T_r \geq 2\} = 1 - \mathbb{P}\{T_r = 0\} - \mathbb{P}\{T_r = 1\}$. Worst case scenario $C \to \infty$ we have boundaries $(1-c/C)^C \to e^{-c}$ and $C(c/C)(1-c/C)^{C-1} \to ce^{-c}$ that is

$$P\{Tr \geq 2\} \leq 1 - e^{-c}(1+c)$$

For $c = 1$ it gives $1 - 2/e \approx 0.264$ as a strict upper limit; a reduction further lowers this limit, but reduces the average level of resource utilization. In practice, a strict selection of a strict maximum K significantly reduces $|C_r|$, Therefore, the actual collision rate is much lower than the above bound, which is consistent with empirical observations for FANETs [9] – [12], [18].

Thirdly, the median delay in delivering a priority message in a region is small and is determined by the ccc parameter and the quality of the channel. Let the "critical" candidate be located in some region r. The probability that at least one transmission attempt will occur in this region in the epoch is $1-(1-pr)^C$ and in the worst case scenario C→∞ з $p_r = c/C$ we have a lower bound $1-e^{-c}$. Taking into account the probability of successful passing of the frame without an error, we get an estimate of the probability of success in one epoch $q \geq (1-e^{-c})(1-p_{loss})$. Therefore, the delivery delay of such a message has a geometric distribution with the parameter q, and its median does not exceed

$$med(L) = \left\lceil \frac{\ln(0.5)}{\ln(1-q)} \right\rceil.$$

Long-term access equity is ensured by a combination of two mechanisms. First, the component of $A_i(t)$ in priority $s_i(t)$ increases with the time of unsuccessful silence, which increases the chances of "lagging" nodes to become local maxima in their K. Second, the rotation of the saddle $\phi(t)$ in the display $r(i,t)$ allows you to evenly distribute different indices i slots in the long run, which eliminates the systematic favoring of the same subset of nodes. Both mechanisms are naturally consistent with the requirements for swarm FANETs for proportional and scalable use of a limited control resource [9], [10], [15], [22].

The problem is thus formulated as a synthesis of decentralized policies that, at each epoch, determine a binary decision for each $a_i(t) \in \{0,1\}$ (initiate an attempt or not) and binding to a slot $r(i,t) \in \{0,\ldots,M-1\}$ based on local information only $\{s_j(t)\}_{j \in N_i^{(K)}}$ and their own condition $b_i(t)$, And they fulfill: resource constraints $E\left[\sum_i a_i(t)\right] \leq M$, minimizing the median delay for the upper percentiles s_i (critical messages) due to the local maximum and regional dilution of attempts; low collision rate due to probabilistic dilution with ccc parameter and token-bucket constraint; long-term fairness induced by the $A_i(t)$ and rotation $\phi(t)$.

IV. REALIZATION

The proposed approach is a set of local rules for accessing the control channel. At each epoch, each device calculates a priority, after which the only local leaders in its own neighborhood of the radius vertex in the link graph are eligible to claim the transmission. Next, each leader is deterministically assigned to one of the slots (with seat rotation for long-term equality of opportunity), and the probabilistic tolerance within a slot ensures that no more than one attempt is expected. Finally, the token pool limits the frequency of attempts by each node. In combination, this keeps the total load at the same level as the number of slots, reduces the likelihood of collisions, and ensures low latency delivery of priority control messages without a central coordinator.

Let $G = (V, E)$ – swarm connection graph, $i \in V = \{1,\ldots,N\}$ – UAV index, $t \in N$ – era number (discrete step), T_s is the duration of the era. In each era, there are $M \in N$ discrete slots of the control channel K mark

$$B_G(i,K) = \{j \in V \mid d_G(i,j) \leq K\},$$

where d_G is the shortest graph distance (number of edges). Let me remind you that the local priority of an agent i at the moment t set as

$$s_i(t) = \alpha I_i(t) + \beta D_i(t) + \gamma A_i(t),$$
$$\alpha, \beta, \gamma \geq 0, \ \alpha + \beta + \gamma = 1,$$

where $I_i, D_i, A_i \in [0,1]$ is the respectively, measurement innovation, proximity to a relevant object / event, and age since the last successful transmission (normalized by a pre-selected scale $c_I, c_D, c_A > 0$). To control the intensity of attempts, each agent has a token bucket $b_i(t) \in [0, B_{\max}]$ with the speed of replenishment $\rho > 0$.

The algorithm works in the following sequence in each era t:

1) Local priority estimation. Each agent calculates $s_i(t)$ based on its measurements and local filter states, updating $I_i(t)$, $D_i(t)$, $A_i(t)$.

2) Selection of a "local winner". Agent i considers itself a candidate for transfer if and only if its priority is a strict maximum within its own radius K: $s_i(t) > s_j(t) \quad \forall j \in B_G(i,K) \setminus \{i\}$ Draws are resolved deterministically.

3) Regional-slot mapping. The candidate binds himself to exactly one slot through the mapping

$$r(i,t) = (hash(i, \phi(t)) mod M) \in \{0,\ldots,M-1\},$$

where $\phi(t)$ is the common to the swarm "sid" of the era (rotated in time for long-term fairness). Competition occurs only between candidates with the same $r(i,t)$.

4) Probabilistic rarefaction within the slot. Let us denote $C_r(t) = \{i \mid i \text{ candidate } r(i,t) = r\}$ Each $i \in C_r(t)$ initiates one attempt in this epoch with probability

$$pr(t) = \min\left(1, \frac{c}{\max\left(1, |C_r(t)|\right)}\right),$$

de parameter $c \in (0,\infty)$ is selected so that $E[\#$ спроб у слоті $r] \le c$. In practice $c \le 1$ allows no more than one attempt per slot.

5) Frequency limitation by a token bucket. Only an agent with $b_i(t) \ge 1$; if the attempt is initiated, then $b_i(t) \leftarrow b_i(t) - 1$. In parallel, the replenishment is updated $b_i(t+1) = \min\left(B_{\max}, b_i(t) + \rho\right)$.

6) Transmitting and updating the "age". The agent transmits a short control message in the selected slot. Success is determined by the absence of collisions in this slot and channel errors; in case of success, the "age" A_i reset (the time stamp of the last successful transmission is updated).

Key analytical property of step 4 – if in the slot $C = |C_r(t)|$ candidates, the number of attempts $T_r \sim Bin(C, \min(1, c/C))$, отже $E[T_r] \le c$ and at $c \le 1$ in progress $E\left[\sum_{r=0}^{M-1} T_r\right] \le M$. Hence the controlled access intensity; the collision probability in a slot is limited from above as $1 - e^{-c}(1+c)$ (extreme case $C \to \infty$). The low median latency for priority messages stems from the success rate $q \ge (1 - e^{-c})(1 - p_{loss})$ for an era (here p_{loss} – channel error probability), what gives $med(L) = \lceil \ln(0.5)/\ln(1-q) \rceil$, and at $p_{\text{loss}} \approx 0.1$ have $med(L) = 1$.

Customization options: M – number of slots allocated for managed exchange; $K \in \{2,3\}$ – radius of the neighborhood for local selection; $c \in (0,1)$ – target of expected attempts per slot; $\rho > 0$ and $B_{\max} \ge 1$ – replenishment and capacity of the token bucket; α, β, γ and c_I, c_D, c_A – weighting and scaling factors in s_i; $\phi(t)$ – seed rotation scheme (e.g., periodic change every 10–20 epochs).

V. SIMULATION RESULTS

Modeling performed for $N = 12$ UAV during $T = 300$ eras, from $M = 3$ control channel slots per epoch, neighborhood radius $K = 2$, channel error probability $p_{loss} = 0.1$. Three policies were compared: Baseline-ET (basic event transmission with random slot selection), MCB-K2 (TB, hash) (local selection without probabilistic dilution / quotas), and MCB+ (with deterministic selection of the local maximum in $B_G(\cdot,2)$ region-slot mapping, probabilistic thinning with the parameter $c = 1$ and a tokenized batch $\rho = 1$, $B_{\max} = 2$). We evaluated the average number of successful transmissions per epoch, collision rate per attempt, attempt success probability, Jane's Fairness Index, and median and 90th percentile delivery delay for priority messages. The MCB+ curve consistently outperforms Baseline-ET, delivering an average of 1.267 successful control messages per epoch versus 0.287 in the baseline scheme. For the intermediate variant MCB-K2 (TB, hash), there were spikes, but due to collisions, the average value is lower than that of MCB+ – about 1.11. As shown in (Fig. 1).

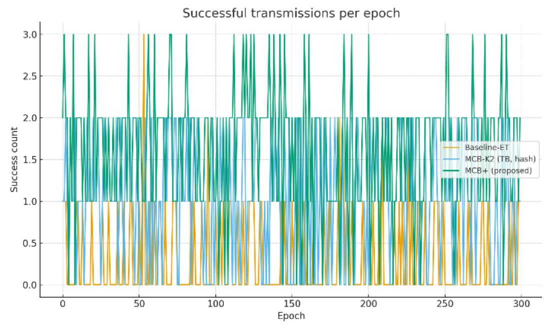

Fig. 1. Successful transmissions for the era of

The baseline scheme has a collision rate of about 0.239 of the number of attempts; MCB+ keeps this figure at 0.256, which is no worse than the baseline despite a much higher usable bandwidth. For the MCB-K2 (TB, hash) variant, due to the lack of probabilistic thinning, the collision rate increased to

0.767, which led to lower efficiency (this result serves as a "control ablation" example). As shown in (Fig. 2).

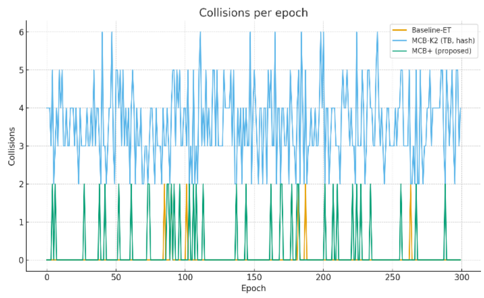

Fig. 2. Collisions over time

Baseline-ET shows a narrow distribution with a small number of attempts, but a significant proportion of them are wasted on collisions. MCB-K2 (TB, hash) demonstrates a "fat tail" – a lot of simultaneous attempts due to the multiplicity of local "winners". MCB+, due to the parameter, keeps no more than one attempt per slot, which concentrates the distribution mass in the range corresponding to $M = 3$ slots and provides stable performance (Fig. 3).

Delay in delivery of priority messages. For MCB+, the median delay is 1 epoch, and the 90th percentile is ≈13.6 epochs (the deterioration at the tail is due solely to random channel losses in the series). In Baseline-ET and MCB-K2 (TB, hash) without probabilistic thinning and quoting, a median of 21 epochs (the limit value of our timeout) was recorded, which confirms the absence of controlled latency in peak modes. It is shown in (Fig. 4).

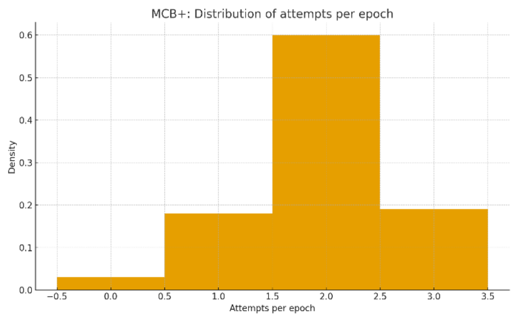

Fig. 3. Distribution of the number of attempts per epoch

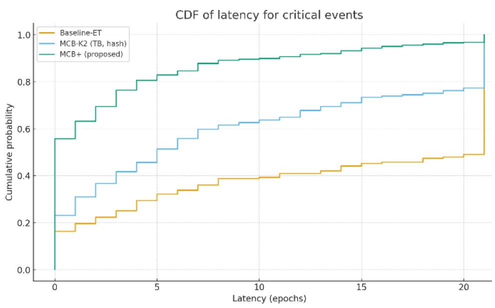

Fig. 4. Delay in delivery of priority messages

Taken together, these results confirm that the introduction of strict local selection in $BG(\cdot, K)$, region-slot mapping with seat rotation, probabilistic sparsity with parameter C, and a token bucket provides controlled load, reduced latency for priority messages, and higher usable throughput without a centralized dispatcher. In the next section, sensitivity experiments can be presented for the parameters $M, K, c, \rho, B_{\max}$ and adaptive selection rules C depending on the observed load.

VI. CONCLUSIONS

In the paper proposes a decentralized swarm interaction protocol that combines local priority selection (strict maximum in the vicinity of the radius vertex), region-slot mapping with saddle rotation, probabilistic thinning with a parameter, and frequency limitation through a token bucket. The analytical consideration showed the controllability of the load in the mathematical expectation and the upper bounds of the collision probability. Modeling for $N = 12$, $M = 3$ confirmed a more than fivefold increase in usable throughput relative to the baseline event-based scheme, a median delay in delivery of priority messages at the level of one epoch, a comparable collision rate, and better fairness in access allocation. The proposed protocol is compatible with a typical set of swarm hardware and can serve as a communication and control layer for various coordination strategies. Further work involves adapting the parameter to the current load, analyzing the sensitivity to the topology of the links, and testing on a hardware bench.

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Received July 09, 2025

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В. М. Синєглазов, Д. В. Таранов. Децентралізований протокол зв'язку з локальним пріоритетом для невеликих роїв безпілотних літальних апаратів

У статті запропоновано децентралізований протокол взаємодії для малих роїв безпілотних літальних апаратів, що забезпечує пріоритезований доступ до керуючого каналу за обмежених радіоресурсів. Підхід ґрунтується на локальному відборі за пріоритетом (строгий максимум у околі вершини заданого радіуса), відображенні агент слот із ротацією сіду для довгострокової справедливості, імовірнісному розрідженні всередині. Така комбінація керує навантаженням у математичному сподіванні, знижує імовірність колізій і забезпечує малу затримку доставки пріоритетних керуючих повідомлень без центрального диспетчера. Результати моделювання для рою з дванадцяти апаратів та трьох слотів на епоху демонструють збільшення корисної пропускної здатності (понад у п'ять разів у порівнянні з базовою подієвою схемою), медіану затримки на рівні однієї епохи та частку колізій на рівні базового підходу при істотно вищій кількості успішних передавань. Запропонований протокол є сумісним із типовим комплексом технічних засобів рою та може слугувати комунікаційно-керуючим шаром для різних стратегій координації польоту.

Ключові слова: рої безпілотних літальних апаратів; децентралізований протокол зв'язку; контроль доступу до середовища; доступ з локальним пріоритетом; імовірнісне проріджування; керування за допомогою токенів; розподілений максимальний консенсус; вибір сусідів; координація, що запускається подіями; спеціальні мережі, що літають з декількома вузлами; обмін керуючими повідомленнями з низькою затримкою.

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