

КОМП'ЮТЕРНІ МЕТОДИ І ЗАСОБИ ІНФОРМАЦІЙНИХ ТЕХНОЛОГІЙ ТА УПРАВЛІННЯ

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COMPARATIVE ANALYSIS OF DATA SYNCHRONIZATION POLICIES FOR ENSURING SURVIVABILITY OF INFORMATION SYSTEMS ON MOBILE PLATFORM

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The paper considers a class of information systems on a mobile platform with intermittent connectivity and dynamic exchange delays [1, 2]. Under such conditions, survivability is considered as the ability of an information system to maintain a correct and recoverable state of data in replicas, despite connection breaks during data retrieval and data update conflicts [3, 4]. The central object of analysis is the data synchronization policy – the rule for choosing the timing, volume and order of reconciliation and the method of merging divergent data versions. In the report, a coherent mathematical framework for comparing policies is built, transparent relationships between their parameters and indicators of lag and conflict are derived, and stable patterns of effectiveness at the level of information system data are formulated.

Let the data model be given as a set of replicas $R = 1, \dots, m$ and a set of keys (data objects) K . Each replica $r \in R$ has a local state $\sigma_r(t)$ at a time t . The change flow is a sequence of operations $\Xi = \xi_1, \xi_2, \dots$, on which a causal order \prec is given. A subset $F_r(t) \subseteq \xi_i : i \leq i(t)$ – consistent with the causal order – is applied at a replica r at a time t . The set of applied operations is causally closed, i.e. if an operation is included, then all its causal predecessors are also included. The merge of versions is defined by an operator m with the properties of associativity, commutativity, and idempotence – with full delivery, this guarantees the convergence of all replicas to a single state. The reference state at time t is given as the composition of all operations in any linear extension of the causal order:

$$\sigma^*(t) = \xi_{i_1} \circ \xi_{i_2} \circ \dots \circ \xi_{i_{i(t)}} \sigma_0, \quad i_1 \prec i_2 \prec \dots \prec i_{i(t)} \quad (1)$$

The lag of a replica r for a key k is the number of operations on this key on r that have not yet been applied to it by the time t . Let $U_{r,k}(t)$ be the operations

on the key k that exist in the global change flow by the time t , but have not yet been applied at the replica r . Then:

$$\delta_{r,k}(t) = |U_{r,k}(t)|, \quad U_{r,k}(t) = \xi_i \text{ на } \partial k : i \leq i(t), \quad \xi_i \notin F_r(t). \quad (2)$$

The weighted lag of a replica is defined as the weighted sum of the lags for all keys with significance weights $w_k > 0$, i.e., how much the lag of this particular key affects the overall lag measure:

$$D_r(t) = \sum_{k \in K} w_k \delta_{r,k}(t). \quad (3)$$

To characterize the conflict, we use the number of cases when two independent operations on the same key arrive in different orders and require merging. For convenience, we introduce the notation of this quantity as $C_r(t)$. The integral quality of the policy π on the interval $0, T$ is defined as the average level of lag taking into account the 'price' of conflict $\lambda \geq 0$:

$$J_\pi(T) = \frac{1}{T} \int_0^T \left(\sum_{r \in R} D_r(t) + \lambda C_r(t) \right) dt. \quad (4)$$

The sensitivity to rare extreme episodes of lag (tail risk measure) relative to the mean

$$\bar{D}_r(T) = \frac{1}{T} \int_0^T \sum_r D_r(t) dt$$

is separately estimated:

$$R'_\alpha(T) = \inf_{z \in \mathbb{R}} \left\{ z + \frac{1}{1-\alpha} \mathbb{E} \left[\bar{D}(T) - z_+ \right] \right\}, \quad 0 < \alpha < 1. \quad (5)$$

Next, a comparison of three generalized families of policies is performed. The periodic policy performs an exchange between a pair of replicas (p, q) at equal time intervals $h > 0$.

If the average intensity of operation occurrence on a key k is equal to λ_k , then the expected lag is approximately equal to the sum of the half-intervals of waiting on the keys:

$$\mathbb{E} D_q(t) \approx \sum_k w_k \frac{\lambda_k h}{2}. \quad (6)$$

The periodic coordination loss functional has a characteristic U -like form.

The first term characterizes the increase in the temporal deviation of the copy relevance between sessions.

The second term is the fixed overhead for each synchronization act.

Then the optimal interval h^* balances these effects:

$$J_{reboot}(h) = c_1 h + \frac{c_2}{h}, \quad h^* = \sqrt{\frac{c_2}{c_1}}, \quad c_1, c_2 > 0. \quad (7)$$

An event-driven policy with a threshold initiates an exchange when the accumulated significance of changes by key k exceeds the threshold θ_k .

Let $s \xi_i \geq 0$ be the significance weight of the operation on k . Then the activation condition has the form:

$$\sum_{\xi_i \in \zeta(k)} s \xi_i \geq \theta_k. \quad (8)$$

For piecewise-stationary flows of changes, the upper bound for the expected lag is:

$$\mathbb{E}D_q(t) \leq \sum_k w_k \left(\frac{\theta_k}{2\bar{s}_k} + \varepsilon_k \theta_k \right), \quad \bar{s}_k = \mathbb{E}s \xi_i, \quad (9)$$

where $\varepsilon_k \theta_k$ is a function that monotonically decreases by θ_k , which reflects the decrease in the threshold activation frequency with increasing θ_k .

The causal-batch policy forms for sending minimal causality 'fronts' of operations that have not yet been applied, without violating causal order.

Given the terminating delivery and a merging operator with the properties of associativity, commutativity, and idempotence, such a policy reduces conflict compared to transmission without causal batching:

$$\mathbb{E}C_q(t) \leq \eta \mathbb{E}C'_q(t), \quad 0 < \eta < 1. \quad (10)$$

The parameter η decreases with an increasing share of dependent (non-parallel) changes in the flow. For any policy, it is useful to prioritize keys by significance weights w_k : if at each synchronization the keys with the largest w_k are served first, then the reduction in the total lag has a lower bound:

$$\Delta D(t) \geq \sum_{k \in K^0} w_k - w_{\min} \mathbb{E}[\delta_{q,k}^\phi(t) - \delta_{q,k}^\varphi(t)]. \quad (11)$$

In (11) ϕ , φ are the values of $\delta_{q,k}(t)$ right before and immediately after the synchronization act, respectively, for the key k .

The paper shows that in the periodic policy, decreasing the interval h linearly reduces the lag (6), but increases the frequency of service procedures – the optimal h^* according to (7) minimizes the loss functional.

In the event-driven policy, there is a working optimum of thresholds θ_k that minimizes the sum of 'accumulated lag between activations + service actions' (9).

That is, a threshold that is too small generates an excessive number of microsessions, and a threshold that is too large accumulates a deviation in relevance.

The causal batching (10) systematically reduces conflicts due to the correct order of arrival of dependent changes, which reduces the need for manual merging. Finally, prioritizing keys by weights w_k makes a guaranteed contribution to reducing the total lag (11), therefore it should be considered as a universal module in any policy.

A practical conclusion for ensuring survivability at the data level is the feasibility of a two-level organization, in which a fast local event-based coordination loop with thresholds and aggregation of small events is combined with a slower background periodic coordination, tuned according to (7) taking into account the intervals of communication interruptions, which reduces the average lag and tail risks and increases the survivability of the system.

References

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EDGE AI FOR REAL-TIME VIDEO ANALYTICS

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The exponential growth of video streams from cameras and IoT devices creates a pressing need for timely, reliable analysis close to the data source. Traditional cloud computing approach is hindered by high bandwidth consumption and high latency [1], which makes it difficult to meet real-time requirements in large-scale deployments. Processing video exclusively in the cloud also raises privacy and security concerns, as raw video data must be transmitted over external networks. Deploying AI inference at the edge - directly on cameras, local gateways, or small on-premise servers - reduces response time, lowers network load, and helps keep sensitive visual data within the local domain.

Edge deployment enables systems to operate with greater autonomy and resilience: devices can continue to detect and report critical events even when network connectivity to the cloud is limited or intermittent. This is particularly