

Errata for “End-to-End Schedulability of Virtualized Distributed Time-Triggered Systems” (RTNS 2024)

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This document corrects errors in the formal system model and correctness constraints of the paper “End-to-End Schedulability of Virtualized Distributed Time-Triggered Systems,” published in the *Proceedings of the 32nd International Conference on Real-Time Networks and Systems (RTNS 2024)*, ACM, pp. 242–254, DOI: [10.1145/3696355.3696364](https://doi.org/10.1145/3696355.3696364). The errors concern the formal statement of the correctness constraints. The schedule synthesis implementation used in the experimental evaluation enforced the intended semantics, so the experimental results and the conclusions of the paper are unaffected. Constraint and section numbers below refer to the published version.

Erratum 1 — Constraint 4 (Unique Assignment Constraint), Section 4.1

The published constraint states, with $\mathcal{P} = \bigcup_{\forall n \in \mathcal{V}, \forall c \in \mathcal{C}^n} \mathcal{P}(c)$ the set of all TT VCPUs:

$$\bigcap_{\forall \rho \in \mathcal{P}} \mathcal{T}(\rho) = \emptyset.$$

The constraint should read:

$$\forall \rho_1, \rho_2 \in \mathcal{P}, \rho_1 \neq \rho_2 : \quad \mathcal{T}(\rho_1) \cap \mathcal{T}(\rho_2) = \emptyset.$$

In addition, if every task is required to be assigned to some VCPU, the condition $\bigcup_{\forall \rho \in \mathcal{P}} \mathcal{T}(\rho) = \mathcal{T}$ must hold. The published paper assumes this assignment as given input.

Erratum 2 — Constraint 6 (End-to-End Constraint), Section 4.2

The end-to-end latency requirement is written $E(\tau_i \xrightarrow{s_h} \tau_j)$ but it must be $E(\tau_i \xrightarrow{s_h} \tau_l)$. Furthermore, since offsets are period-relative and the tasks share a period, the constraint as written couples every receiver job with every sender job which is strictly stronger than the per-instance latency requirement, so it is safe but over-constraining. In the implementation we set $j = m$ which can also be added optionally to the constraint.

Erratum 3 — Helper set $\mathcal{O}_{ij}$, Section 4.3

Two corrections apply.

- (a) **Helper set $\mathcal{O}_{ij}$.** First, the lower bound of the published set compares against the unscaled offset $z_{ij} \cdot \phi$, which must be scaled by the microtick, $z_{ij} \cdot \phi \cdot \mu_c$, as in the upper bound. Second, the lower bound must include the VCPU switching overhead $\delta_\rho(c)$, which the schedule

synthesis in Section 5 reserves at the start of every VCPU segment. The corrected helper set is:

$$\mathcal{O}_{ij} = \left\{ x_{lmn} \mid \forall \tau_l \in \mathcal{T}(\rho_i), J_{lm} \in \mathcal{J}_l, x_{lmn} \in \mathcal{X}_{lm} \text{ s.t.} \right. \\ \left. (x_{lmn} \cdot \phi \cdot \mu_c + m \cdot T_l \geq z_{ij} \cdot \phi \cdot \mu_c + \delta_\rho(c)) \wedge \right. \\ \left. (x_{lmn} \cdot \phi \cdot \mu_c + m \cdot T_l + x_{lmn} \cdot L \leq z_{ij} \cdot \phi \cdot \mu_c + z_{ij} \cdot L) \right\}$$

(b) **Missing containment constraint.** The following constraint, which the schedule synthesis in Section 5 enforces by construction, must be added:

Constraint 16 (Task Segment Containment Constraint). *Given the virtualized distributed real-time system defined by the graph $G(\mathcal{V}, \mathcal{L})$, we have:*

$$\forall n \in \mathcal{V}, \forall c \in \mathcal{C}^n, \forall \rho_i \in \mathcal{P}(c), \forall \tau_l \in \mathcal{T}(\rho_i), \forall J_{lm} \in \mathcal{J}_l, \forall x_{lmn} \in \mathcal{X}_{lm} : \quad \exists z_{ij} \in \mathcal{Z}_i : x_{lmn} \in \mathcal{O}_{ij}$$

The constraint is numbered 16 to avoid renumbering the published constraints. The two references to “Constraints 1 to 15” in Section 5 should consequently read “Constraints 1 to 16.”

Erratum 4 — Constraint 12 (Frame Constraint), Section 4.4.1

The constraint should read:

$$\forall s_i \in \mathcal{S}, \forall (x, y) \in s_i, \forall J_{ij}^{xy} \in \mathcal{J}_i^{xy}, \forall f_{ijk}^{xy} \in \mathcal{F}_{ij}^{xy} : \quad (f_{ijk}^{xy} \cdot \phi \cdot \mu_x \geq 0) \wedge (f_{ijk}^{xy} \cdot \phi \cdot \mu_x + f_{ijk}^{xy} \cdot L \leq T_i)$$

Erratum 5 — Constraint 15 (Frame Isolation Constraint), Section 4.4.2

The published constraint quantifies over a single link $\forall (x, y) \in \mathcal{L}$ and frames $f_{ijk}^{xy} \in \mathcal{F}_{ij}^{xy}$, $f_{lmn}^{xy} \in \mathcal{F}_{lm}^{xy}$, while its body refers to frames f^{ab} , f^{xa} , and f^{ya} on links (a, b) , (x, a) , and (y, a) , with a and b unbound, and with y , bound as the endpoint of the quantified link (x, y) , reused in a different role. Furthermore, the final disjunct $P_i^{ab} \neq P_j^{ab}$ compares the egress port of stream s_i with that of job index j instead of stream s_l , and the term $f_{lmn}^{ya} \cdot \mu_y$ is missing the offset selector $\cdot \phi$. The constraint applies to two streams converging on a device a via links (x, a) and (y, a) and sharing the egress link (a, b) , and should read:

$$\forall a, b, x, y \in \mathcal{V}, \forall s_i, s_l \in \mathcal{S}, i \neq l, \text{ s.t. } (x, a), (a, b) \in s_i \wedge (y, a), (a, b) \in s_l, \\ \forall J_{ij}^{ab} \in \mathcal{J}_i^{ab}, \forall J_{lm}^{ab} \in \mathcal{J}_l^{ab}, \forall f_{ijk}^{xa} \in \mathcal{F}_{ij}^{xa}, \forall f_{ijk}^{ab} \in \mathcal{F}_{ij}^{ab}, \forall f_{lmn}^{ya} \in \mathcal{F}_{lm}^{ya}, \forall f_{lmn}^{ab} \in \mathcal{F}_{lm}^{ab} : \\ \left(f_{lmn}^{ab} \cdot \phi \cdot \mu_a + m \cdot T_l + \Pi \leq f_{ijk}^{xa} \cdot \phi \cdot \mu_x + j \cdot T_i + \Delta^{xa} \right) \vee \\ \left(f_{ijk}^{ab} \cdot \phi \cdot \mu_a + j \cdot T_i + \Pi \leq f_{lmn}^{ya} \cdot \phi \cdot \mu_y + m \cdot T_l + \Delta^{ya} \right) \vee \left(P_i^{ab} \neq P_l^{ab} \right)$$

Erratum 6 — VCPU segment construction in EDF-SMT, Section 5

For an ordered set $\mathcal{X}(z_{ij}) = \{x_1, \dots, x_m\}$ of consecutive job segments sharing a VCPU segment z_{ij} , the published text derives the VCPU segment’s offset and size as $z_{ij} \cdot \phi = x_1 \cdot \phi - \delta_\rho(c)$ and $z_{ij} \cdot L = x_m \cdot \phi + x_m \cdot L$. The size must read:

$$z_{ij} \cdot L = x_m \cdot \phi + x_m \cdot L - z_{ij} \cdot \phi = x_m \cdot \phi + x_m \cdot L - x_1 \cdot \phi + \delta_\rho(c).$$

As in Section 5.2 of the paper, offsets and lengths are expressed here in a common unit, i.e., the microtick scaling of Section 4 is omitted ($\mu_c = 1$). With explicit scaling, the two expressions read $z_{ij} \cdot \phi \cdot \mu_c = x_1 \cdot \phi \cdot \mu_c - \delta_\rho(c)$ and $z_{ij} \cdot L = (x_m \cdot \phi - x_1 \cdot \phi) \cdot \mu_c + x_m \cdot L + \delta_\rho(c)$.

Erratum 7 — Clarifications, Section 4.3

Let T_{HP} denote the hyperperiod of the system. The correctness constraints implicitly assume that every VCPU segment lies within the hyperperiod, i.e.,

$$\forall n \in \mathcal{V}, \forall c \in \mathcal{C}^n, \forall \rho_i \in \mathcal{P}(c), \forall z_{ij} \in \mathcal{Z}_i : \quad z_{ij} \cdot \phi \cdot \mu_c + z_{ij} \cdot L \leq T_{HP},$$

and that every task job segment lies within its period instance, which follows from Constraint 1 whenever $D_i \leq T_i$. Neither Constraint 3 nor Constraint 9 checks overlaps across the hyperperiod boundary, so both assumptions are required for the constraints to be exhaustive.

Erratum 8 — Constraint 14 (Flow Transmission Constraint), Section 4.4.1

The published constraint reads

$$\begin{aligned} \forall s_i \in \mathcal{S}, \forall (a, x), (x, b) \in s_i, \forall J_{ij}^{ax} \in \mathcal{J}_i^{ax}, \forall J_{ij}^{xb} \in \mathcal{J}_i^{xb}, \forall f_{ijk}^{ax} \in \mathcal{F}_{ij}^{ax}, \forall f_{ijk}^{xb} \in \mathcal{F}_{ij}^{xb} : \\ f_{ijk}^{xb} \cdot \phi \cdot \mu_x - \Delta^{xb} - \Pi \geq f_{ijk}^{ax} \cdot \phi \cdot \mu_a + f_{ijk}^{ax} \cdot L. \end{aligned}$$

As stated in the accompanying text, a frame may be forwarded on link (x, b) only after it has been fully received over the preceding link (a, x) . The delay to account for is therefore the propagation delay of the incoming link, Δ^{ax} , not that of the outgoing link, Δ^{xb} , consistent with the use of Δ^{yb} in Constraint 7 and of Δ^{xa} , Δ^{ya} in Constraint 15. The constraint should read:

$$\begin{aligned} \forall s_i \in \mathcal{S}, \forall (a, x), (x, b) \in s_i, \forall J_{ij}^{ax} \in \mathcal{J}_i^{ax}, \forall J_{ij}^{xb} \in \mathcal{J}_i^{xb}, \forall f_{ijk}^{ax} \in \mathcal{F}_{ij}^{ax}, \forall f_{ijk}^{xb} \in \mathcal{F}_{ij}^{xb} : \\ f_{ijk}^{xb} \cdot \phi \cdot \mu_x - \Delta^{ax} - \Pi \geq f_{ijk}^{ax} \cdot \phi \cdot \mu_a + f_{ijk}^{ax} \cdot L. \end{aligned}$$

The two formulations coincide when all links have the same propagation delay, as in the experimental evaluation.

Erratum 9 — Constraint 7 (Task Alignment Constraint), Section 4.2

Two corrections apply.

- (a) **Unbound link endpoints.** The constraint refers to frames f_{hkl}^{ax} and f_{hkl}^{yb} on links (a, x) and (y, b) , but x and y are not bound by the quantifier prefix. They denote the first hop after the sender node a and the last hop before the receiver node b on the route of s_h . The quantifier prefix should read:

$$\begin{aligned} \forall a, b \in \mathcal{V}, \forall c_a \in \mathcal{C}^a, \forall c_b \in \mathcal{C}^b, \forall \rho_a \in \mathcal{P}(c_a), \forall \rho_b \in \mathcal{P}(c_b), \\ \forall \tau_i \in \mathcal{T}(\rho_a), \tau_j \in \mathcal{T}(\rho_b) \text{ s.t. } \tau_i \xrightarrow{s_h} \tau_j, \\ \forall (a, x), (y, b) \in s_h \text{ s.t. } (a, x) \text{ is the first and } (y, b) \text{ the last link of } s_h, \\ \forall J_{ik} \in \mathcal{J}_i, \forall J_{jk} \in \mathcal{J}_j : \end{aligned}$$

The body of the constraint is unchanged.

- (b) **Typographical correction.** In the paragraph preceding Constraint 7, “Furthermore, we have to align the transmission schedule of the stream s_k along its route” must read “... of the stream s_h along its route” (the constraint binds s_h).