Supplementary Material for the Paper: "Deterministic Multicast Using Temporal Graph-based Routing and Scheduling in Non-terrestrial Networks"

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In this document, we present the detailed derivations for ***Lemma* 1**, ***Application***, ***Theorem* 1**, and ***Theorem* 2**.

Appendix A
Proof of *Lemma* 1

We verify ***Lemma* 1** using proof by contradiction. Assume that the task data is transmitted along a loop consisting of the links $(v,w),(w,r),(r,p),\ldots,(q,u)$ and (u,v). According to Equation (10), we can obtain: $L(w)=(h_{v,w}-1)\cdot|\tau|+l_{v,w}^{h_{v,w}}$, $L(r)=(h_{w,r}-1)\cdot|\tau|+l_{w,r}^{h_{w,r}}$, $L(p)=(h_{r,p}-1)\cdot|\tau|+l_{r,p}^{h_{r,p}}$,..., $L(u)=(h_{q,u}-1)\cdot|\tau|+l_{q,u}^{h_{q,u}}$ and $L(v)=(h_{u,v}-1)\cdot|\tau|+l_{u,v}^{h_{u,v}}$, where $h_{v,w}$, $h_{w,r}$, $h_{r,p}$,..., $h_{q,u}$ and $h_{u,v}$ represent the cycles within which task data transmitted along different links, and $l_{v,w}^{h_{v,w}}$, $l_{w,r}^{h_{w,r}}$, $l_{r,p}^{h_{r,p}}$,..., $l_{q,u}^{h_{q,u}}$ and $l_{u,v}^{h_{u,v}}$ denote the delay of these links. Since link delays are nonnegative, it follows that: $(h_{v,w}-1)\cdot|\tau|<L(w)$, $(h_{w,r}-1)\cdot|\tau|<L(r)$, $(h_{r,p}-1)\cdot|\tau|<L(p)$,..., $(h_{q,u}-1)\cdot|\tau|<L(u)$ and $(h_{u,v}-1)\cdot|\tau|<L(v)$. According to Inequality (12), $L(v)\le(h_{v,w}-1)\cdot|\tau|$, $L(w)\le(h_{w,r}-1)\cdot|\tau|$, $L(r)\le(h_{r,p}-1)\cdot|\tau|$,..., $L(q)\le(h_{q,u}-1)\cdot|\tau|$, and $L(u)\le(h_{u,v}-1)\cdot|\tau|$ hold. Combining the above inequality groups, we derive two key results:

- On one hand, $h_{v,w}<h_{w,r}$, $h_{w,r}<h_{r,p}$, $\ldots$, and $h_{q,u}<h_{u,v}$ hold, indicating that $h_{v,w}<h_{u,v}$.
- On the other hand, $(h_{u,v}-1)\cdot|\tau|<L(v)$ and $L(v)\le(h_{v,w}-1)\cdot|\tau|$ hold, implying that $h_{u,v}<h_{v,w}$.

Since the two results are contradictory, the initial assumption does not hold. Therefore, we conclude that the task data transmission is loop-free. The proof is thus complete.

Appendix B
Application of Algorithm 1

As illustrated in Fig. 1(a), the input of **Algorithm 1** consists of the pruned and enhanced time-expanded graph (TEG) $\mathcal{G}$ and a time-critical (TC) multicast task denoted as $m=\langle s,\{d_1,d_2\},33.33\text{ms},0.3\text{Mb},1\text{ms},11\text{ms}\rangle$. The detailed procedure of **Algorithm 1** is described as follows:

- **Initialization process.** The desired time-featured (TF) tree $\mathcal{T}$ is initialized as $\emptyset$. The "pend-capacity" $C(\cdot)$ is set to ∞ for s^1 and to 0 for all other nodes. The "arrival-time" $L(\cdot)$ is initialized to 1ms for s^1 and to ∞ for all other nodes. In addition, the "pre-node" $P(\cdot)$ of each node is set to NULL, and the priority queue Q is initialized to contain the entire node set $\mathcal{V}$.
- **Search process.** In **Iteration 1**, node s^1 is extracted from Q due to its maximal "pending-capacity", $C(s^1)=\infty$. Since the storage edge (SE) (s^1,s^2) is the only outgoing edge from s^1, the parameters of s^2 are updated as $C(s^2)=\infty$, $L(s^2)=2$ms, and $P(s^2)=s^1$ (steps 13–15). In **Iteration 2**, node s^2 is popped from Q. Considering the transmission edge (TE) (s^2,w^2) from s^2, the arrival cycle number of the task data transmitted along it is determined as $I(w)=3$. Consequently, the actual arrival node through cross-cycle transmission is w^3, whose "pending-capacity" is improved from 0 to 2Mb, together with updated parameters $L(w^3)=5$ms and $P(w^3)=s^2$ (steps 6–11). Furthermore, by checking the SE (s^2,s^3), we obtain $C(s^3)=\infty$, $L(s^3)=4$ms, and $P(s^3)=s^2$. During **Iterations 3–6**, nodes s^3, s^4 ($C(s^4)=\infty$, $L(s^4)=6$ms, $P(s^4)=s^3$), s^5 ($C(s^5)=\infty$, $L(s^5)=8$ms, $P(s^5)=s^4$), and s^6 ($C(s^6)=\infty$, $L(s^6)=10$ms, $P(s^6)=s^5$) are sequentially selected. In **Iteration 9**, node w^3 is extracted from Q. Due to the violation of the *forwarding time constraint* (step 6), the two TEs, (w^3,v^3) and (w^3,d_1^3), are not visited. However, through TE (w^3,w^4), the parameters of w^4 are updated to $C(w^4)=2$Mb, $L(w^4)=6$ms, and $P(w^4)=w^3$. In **Iteration 10**, the TE (w^4,v^4) is first examined, yielding $C(v^5)=2$Mb, $L(v^5)=9$ms, and $P(v^5)=w^4$. Subsequently, the TE (w^4,d_1^4) is checked, obtaining $C(d_1^4)=1$Mb, $L(d_1^4)=7$ms, and $P(d_1^4)=w^4$. Finally, the SE (w^4,w^5) is examined, resulting in $C(w^5)=2$Mb, $L(w^5)=8$ms, and $P(w^5)=w^4$. In **Iteration 11**, node v^5 is selected as the relay, updating the parameters of v^6 to $C(v^6)=2$Mb, $L(v^6)=10$ms, and $P(v^6)=v^5$. In **Iteration 12**, node v^6 is popped, and its unique outgoing edge (v^6,d_2^6) is checked, resulting in $C(d_2^6)=1$Mb, $L(d_2^6)=11$ms, and $P(d_2^6)=v^6$. In **Iteration 13**, node w^5 with $C(w^5)=2$Mb is extracted from Q. It is determined that the "pending-capacity" of v^6 cannot be further improved through cross-cycle transmission along TE (w^5,v^5) (step 8). In contrast, the parameters of w^6 are updated to $C(w^6)=2$Mb, $L(w^6)=10$ms, and $P(w^6)=w^5$. Subsequently, w^6 is selected in **Iteration 14** without triggering any parameter updates for other nodes. In **Iterations 15** and **16**, nodes d_1^4 and d_2^6 are selected, producing the corresponding virtual nodes d_1' and d_2' with parameters $C(d_1')=1$Mb, $L(d_1')=7$ms, $P(d_1')=d_1^4$; and $C(d_2')=1$Mb,

$L(d_2') = 11\text{ms}$, $P(d_2') = d_2^6$, respectively. In the **final two iterations**, nodes d_1' and d_2' are extracted from Q, indicating that their "pending-capacities" have been maximized, and the **search process** terminates.

- **Construction process.** Since both $C(d_1') > 0$ and $C(d_2') > 0$ are satisfied, the final $\mathcal{T}$ can be constructed through backtracking (steps 21-31). The resulting tree is $\mathcal{T} = (s^1, s^2), (s^2, w^2), (w^3, w^4), (w^4, d_1^4), (w^4, v^4), (v^5, v^6), (v^6, d_2^6)$, as illustrated in Fig. 1(b).

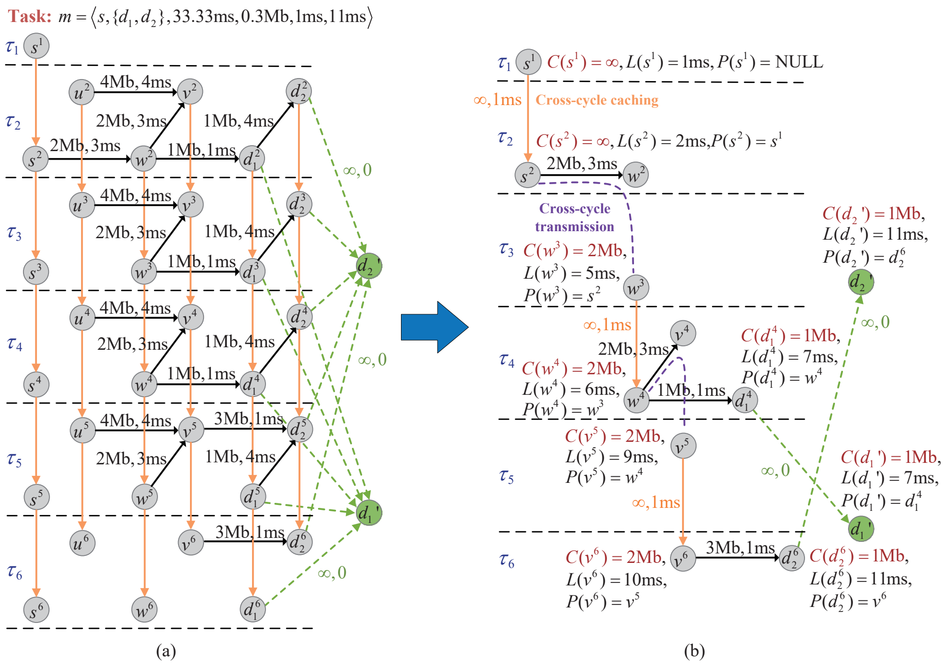
Task: $m = \langle s, \{d_1, d_2\}, 33.33\text{ms}, 0.3\text{Mb}, 1\text{ms}, 11\text{ms} \rangle$
τ_1 τ_2 τ_3 τ_4 τ_5 τ_6
4Mb, 4ms
2Mb, 3ms
1Mb, 4ms
1Mb, 1ms
3Mb, 1ms
∞, 0
$C(s^1) = \infty, L(s^1) = 1\text{ms}, P(s^1) = \text{NULL}$
∞, 1ms
Cross-cycle caching
$C(s^2) = \infty, L(s^2) = 2\text{ms}, P(s^2) = s^1$
Cross-cycle transmission
$C(w^3) = 2\text{Mb}$, $L(w^3) = 5\text{ms}$, $P(w^3) = s^2$
$C(w^4) = 2\text{Mb}$, $L(w^4) = 6\text{ms}$, $P(w^4) = w^3$
$C(d_1^4) = 1\text{Mb}$, $L(d_1^4) = 7\text{ms}$, $P(d_1^4) = w^4$
$C(v^5) = 2\text{Mb}$, $L(v^5) = 9\text{ms}$, $P(v^5) = w^4$
$C(v^6) = 2\text{Mb}$, $L(v^6) = 10\text{ms}$, $P(v^6) = v^5$
$C(d_2^6) = 1\text{Mb}$, $L(d_2^6) = 11\text{ms}$, $P(d_2^6) = v^6$
$C(d_2') = 1\text{Mb}$, $L(d_2') = 11\text{ms}$, $P(d_2') = d_2^6$
$C(d_1') = 1\text{Mb}$, $L(d_1') = 7\text{ms}$, $P(d_1') = d_1^4$
(a)
(b)

Fig. 1. (a) The input of the proposed algorithm; (b) the constructed TF tree.

APPENDIX C
PROOF OF THEOREM *Theorem* 1

For **Algorithm 1**, the key is to demonstrate that each node extracted from $\mathcal{Q}$ has determined its maximum "pending-capacity" $C(\cdot)$. This assertion remains valid for $s^{\check{h}}$ with $C(s^{\check{h}}) = \infty$. Moving on to the K-th extracted node, denoted as u^h (or d_n'), we identify that its "pending-capacity" cannot be further improved by relaying via any node out of $\mathcal{Q}$ (steps 8 to 9, 13 to 14, and 16 to 17). Regarding potential relaying via a node in $\mathcal{Q}$, we adopt proof by contradiction for analysis, accounting for three cases:

i) If reaching u^h via $w^i \in \mathcal{Q}$ along $(w^i, u^i) \in \mathcal{E}_t$ enables $C(u^h) < \min\left\{C(w^i), c_{w,u}^i\right\} \leq C(w^i)$, where $h = \left\lceil \frac{1}{|\tau|} \cdot ((i-1) \cdot |\tau| + l_{w,u}^i) \right\rceil$, a contradiction arises because $C(w^i) \leq C(u^h)$ is enforced by step 4;

ii) If reaching u^h via $u^{h-1} \in \mathcal{Q}$ along $(u^{h-1}, u^h) \in \mathcal{E}_s$ enables $C(u^h) < \min\left\{C(u^{h-1}), c_{u,u}^h\right\} = C(u^{h-1}$, a contradiction also arises due to $C(u^{h-1}) \leq C(u^h)$;

iii) If reaching d_n' via $d_n^i \in \mathcal{Q}$ along $(d_n^i, d_n') \in \mathcal{E}_v$ enables $C(d_n') < \min\left\{C(d_n^i), c_{d_n, d_n'}^i\right\} = C(d_n^i)$, it encounters a contradiction with $C(d_n^i) \leq C(d_n')$.

Therefore, the "pending-capacity" of the K-th extracted node cannot be improved.

Intuitively, the bottleneck capacity of the output TF tree $\mathcal{T}$, calculated as $C(\mathcal{T}) = \min_{(u^h, v^h) \in \mathcal{T}} c_{u,v}^h = \min_{d_n' \in \mathcal{V}_v} C(d_n')$, must reach its maximum since each $C(d_n')$ is maximized when the algorithm terminates. Additionally, the input $\mathcal{G}$ has ensured that $\mathcal{T}$ does not contain edges with insufficient capacity or unsatisfied delay, and step 6 enforces the correct forwarding timing at each hop.

The proof is completed.

APPENDIX D
PROOF OF THEOREM *Theorem* 2

In **Algorithm 1**,we assume that the input $\mathcal{G}$ and the introduced $\mathcal{Q}$ are stored in an adjacency list and a binary heap, respectively. The initialization in step 2 takes $O(|\mathcal{V}|)$ time. During each iteration from steps 3 to 19, it requires $O(1)$ time to extract the node u^h with the maximum bottleneck capacity from $\mathcal{Q}$ and $O(\log|\mathcal{V}|)$ time to update $\mathcal{Q}$ (in step 4). Furthermore, examining each edge (i.e., transmission edge, storage edge, or virtual edge) and updating the parameters (i.e., "pending-capacity" $C(\cdot)$, "arrival-time" $L(\cdot)$, and "pre-node" $P(\cdot)$) of the node actually reached along that edge takes $O(\log|\mathcal{V}|)$ time. Denoting the out-degree of u^h as $\deg(u^h)$, the time complexity of the process from step 5 to 18 is at most $O(\deg(u^h) \cdot \log|\mathcal{V}|)$. At worst, we must traverse all nodes in $\mathcal{V}$ once before extracting all the virtual nodes $d_n' \in \mathcal{V}_v$ from $\mathcal{Q}$. Therefore, the time complexity reaches $O\left(\sum_{u^h \in \mathcal{V}} \deg(u^h) \cdot \log|\mathcal{V}|\right) = O(|\mathcal{E}| \cdot \log|\mathcal{V}|)$. Additionally, the backtracking process takes at most $O(|\mathcal{E}|)$ time. Thus, the time complexity of **Algorithm 1** can be calculated as $O(|\mathcal{V}| + |\mathcal{E}| \cdot \log|\mathcal{V}| + |\mathcal{E}|)$. Since $\mathcal{G}$ is a connected graph, it follows that $|\mathcal{E}| + 1 \geq |\mathcal{V}| \geq 2$ holds, and the time complexity can be further simplified to $O(|\mathcal{E}| \cdot \log|\mathcal{V}|)$. The proof is completed.