Generation and Maintenance of 2-hop Labels for Accelerating Group Steiner Tree Search on Graphs

The road map of this supplement is as follows.

- In Section S1, we provide proofs that are omitted in the main contents.
- In Section S2, we provide detailed discussions on complexities of algorithms.

S1. PROOFS OF THEOREMS

We demonstrate theorems and proofs as follows.

Theorem 1. *A set of 2-hop labels that satisfies the GST-customized 2-hop cover constraint supports the query of a shortest path between every pair of a vertex $v \in V$ and a candidate vertex group $g \in \Gamma_{all}$.*

Proof. We show that we can query the shortest distance/path between every pair of a vertex $v \in V$ and a candidate vertex group $g \in \Gamma_{all}$ using a set L of 2-hop labels that satisfies the above constraint as follows. There are two different cases:

1. Case 1: there is a path between v and g on the original graph. Since each mock edge weight M is larger than the total weight of all non-mock edges, a shortest path between v and v_g on the transformed graph contains a shortest path between v and g on the original graph. Since $|\{v, v_g\} \cap D| < 2$, there is a common hub vertex $u \in C(v) \cap C(v_g)$ in a shortest path between v and v_g. Thus, we can use L to query the shortest distance between v and v_g, which is smaller than $2M$ and equals the shortest distance between v and g on the original graph plus M. Hence, equivalently, we can use L to query the shortest distance between v and g. Furthermore, since there is no mock vertex in the middle of a shortest path between v and v_g on the transformed graph, we can also iteratively query the shortest path between v and g on the original graph by adding predecessors into labels.
2. Case 2: there is no path between v and g on the original graph. Thus, v and v_g are not properly connected, and there may not be a common hub vertex $u \in C(v) \cap C(v_g)$. If there is no common hub vertex $u \in C(v) \cap C(v_g)$, then we can directly deduce that there is no path between v and g on the original graph. If there is a common hub vertex $u \in C(v) \cap C(v_g)$, then since v and v_g are not properly connected on the transformed graph, there must be at least one mock vertex in the middle of any path between v and v_g, and as a result the queried distance of any path between v and v_g is no smaller than $2M$, which still indicates that there is no path between v and g on the original graph.

Hence, this theorem holds. □

Theorem 2. *A set of 2-hop labels that has the GST-customized canonical property is minimal for meeting the GST-customized 2-hop cover constraint.*

Proof. Consider a set L of 2-hop labels that has the GST-customized canonical property. For every pair of properly connected vertices v_i and v_j such that $|\{v_i, v_j\} \cap D| < 2$, let v_k be the vertex with the highest rank in all shortest paths between v_i and v_j. We have $v_k \notin D$ and $v_k \in C(v_i) \cap C(v_j)$, since v_k has the highest rank in all shortest paths between v_i and v_k, as well as between v_j and v_k, and no vertices in these shortest paths can be hubs of v_k, except itself. Thus, L meets the GST-customized 2-hop cover constraint. Moreover, consider an arbitrary label $(v_i, d_{v_i v_j}) \in L(v_j)$. We have (i) v_i and v_j are properly connected; (ii) $|\{v_i, v_j\} \cap D| < 2$; and (iii) the rank of v_i is the highest among all vertices in all shortest paths between v_i and v_j. Thus, there is no other vertex $v_k \in C(v_i) \cap C(v_j)$ in a shortest path between v_i and v_j, *i.e.*, deleting this arbitrary label makes L not satisfy the GST-customized 2-hop cover constraint any more. Hence, this theorem holds. □

Theorem 3. *The set L of 2-hop labels generated by* HL4GST *has the GST-customized canonical property, and thus is minimal for meeting the GST-customized 2-hop cover constraint.*

Proof. Let L^{can} be the set of labels that has the GST-customized canonical property. We prove that every label in L^{can} is also in L as follows.

Consider an arbitrary label $(u, d_{vu}) \in L^{can}(v)$. We observe that (i) u and v are properly connected; (ii) $|\{u, v\} \cap D| < 2$; and (iii) the rank of u is the highest among all vertices in all

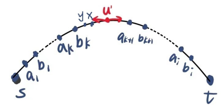

Fig. S1. A illustration for the correctness proofs of the proposed maintenance algorithms.

shortest paths between u and v. Thus, we have $d_{vu} < 2M$, and the generation of the above label cannot be pruned by GST-customized pruning technique in Line 11 of HL4GST. Further consider the labeling process for hub u in HL4GST. HL4GST generates labels with hub u by spreading u to other vertices, starting from u, via a Dijkstra-style process. Suppose that the spread of hub u to v along a shortest path between u and v stops at a middle vertex v' due to the query pruning technique in Line 6 of HL4GST. This means that, before inserting $(u, d_{v'u})$ into $L'(v')$, the queried distance between u and v' is no larger than $d_{v'u}$. As a result, there must be a common hub vertex $z \in C(u) \cap C(v')$ such that z is in a shortest path between u and v', and $r(z) > r(u)$. This contradicts with the fact that the rank of u is the highest among all vertices in all shortest paths between u and v'. Consequently, the spread of hub u to v along a shortest path between u and v cannot stop at a middle vertex, and as a result HL4GST inserts (u, d_{vu}) into $L'(v)$.

We further show that HL4GST also inserts (u, d_{vu}) into $L(v)$ as follows. When it checks $(u, d_{vu}) \in L'(v)$ in Line 18 during the cleaning process, it computes $d'(u, v)$ using $L'_{>r(u)}(v)$ and $L'(u)$. If $d'(u, v) \leq d_{vu}$, then there must be a common hub vertex $z \in C(u) \cap C(v)$ such that z is in a shortest path between u and v, and $r(z) > r(u)$. This contradicts with the fact that the rank of u is the highest among all vertices in all shortest paths between u and v. Consequently, $d'(u, v) > d_{vu}$ and HL4GST also inserts (u, d_{vu}) into $L(v)$. Hence, every label in L^{can} is also in L.

We further prove that every label not in L^{can} is not in L as follows. Suppose that there is a label $(u, d_{vu}) \in L(v) \setminus L^{can}(v)$. We observe that (i) u and v are not properly connected; or (ii) $|\{u, v\} \cap D| = 2$; or (iii) the rank of u is not the highest among all vertices in all shortest paths between u and v. If u and v are not properly connected or $|\{u, v\} \cap D| = 2$, then $d_{vu} \geq 2M$, and the generation of the above label will be pruned by GST-customized pruning technique in Line 11 of HL4GST, which means that $(u, d_{vu}) \notin L(v)$. Otherwise, we consider the case where the rank of u is not the highest among all vertices in all shortest paths between u and v as follows. Let z be the vertex with the highest rank in all shortest paths between u and v. We have $(z, d_{zv}) \in L'_{>r(u)}(v)$ and $(z, d_{zu}) \in L'(u)$. As a result, HL4GST computes $d'(u, v)$ as a larger value than d_{vu} in Line 19, and does not insert (u, d_{vu}) into L. Hence, every label not in L^{can} is not in L. In conclusion, we have $L^{can} = L$. By Theorem 2, this theorem holds. ◻

Theorem 4. *Given a graph and a corresponding set of 2-hop labels that satisfies the GST-customized 2-hop cover constraint, after a batch of edge insertions and edge weight decreases, the maintained set of labels by* BatchM4GST-Insert *satisfies the above constraint for the updated graph.*

Proof. Consider a pair of vertices s and t, we use $p'(s, t)$ to denote a shortest path between s and t after the change. Let u' be the vertex with the highest rank in all shortest paths between s and t after the change, and $u' \in p'(s, t)$. Also let $d'(s, t)$ be the shortest distance between s and t after the change. Suppose that $|\{s, t\} \cap D| < 2$ and $d'(s, t) < 2M$, *i.e.*, s and t are properly connected after the change.

Let $E_{in} = \{(a_1, b_1), ..., (a_i, b_i)\}$ be the set of changed edges on $p'(s, t)$, *i.e.*, $E_{in} \subseteq E_c$. Notably, E_{in} could be empty. Without loss of generality, suppose that a_x is closer to s than b_x along $p'(s, t)$ for each $x \in [1, i]$, and u' is between (a_k, b_k) and (a_{k+1}, b_{k+1}), as illustrated in Figure S1. Since there are only edge insertions and edge weight decreases, $p'(u', b_k)$ is a shortest path between u' and b_k both before and after the change, and u' has the highest rank in all shortest paths between u' and b_k both before and after the change. We also have $|\{u', b_k\} \cap D| < 2$ and $d'(u', b_k) < 2M$.

Suppose that u' is not a hub of b_k before the maintenance. Since the given set of 2-hop labels satisfies the GST-customized 2-hop cover constraint, to correctly query $d'(u', b_k)$, there must be a vertex z such that $z \in C(u') \cap C(b_k)$, $r(z) > r(u')$, and z is in a shortest path between u' and b_k. This contradicts with the assumption that u' has the highest rank in all shortest paths between u' and b_k. Thus, $(u', d'(b_k, u')) \in L(b_k)$, and further $(u', d'(a_{k+1}, u')) \in L(a_{k+1})$, before the maintenance. BatchM4GST-Insert calls $DIFFUSE$ to re-spread hub u' from b_k to s, and from a_{k+1} to t, along $p'(s, t)$. Thus, $(u', d'(s, u')) \in L(s)$, and similarly $(u', d'(t, u')) \in L(t)$, after the maintenance. Hence, for every pair of properly connected vertices v_i and v_j such that $|\{v_i, v_j\} \cap D| < 2$, there is a common hub vertex $u \in C(v_i) \cap C(v_j)$ on a shortest path between v_i

and v_j, *i.e.*, the maintained set of labels by BatchM4GST-Insert still satisfies the GST-customized 2-hop cover constraint. This theorem holds. □

Theorem 5. *Given a graph and a corresponding set of 2-hop labels that satisfies the GST-customized 2-hop cover constraint, after a batch of edge deletions and edge weight increases, the maintained set of labels by* BatchM4GST-Delete *satisfies the above constraint for the updated graph.*

Proof. We use the notations in the proof of Theorem 4. Consider an arbitrary label $(z, d(z, y)) \in L(y)$ before the change. If this label corresponds to a path that passes through a changed edge, *i.e.*, $d'(z, y) \geq d(z, y)$, then BatchM4GST-Delete must call $SPREAD_1$ to set $L(y)[z]$ to ∞.

Subsequently, consider a pair of vertices s and t such that $|\{s, t\} \cap D| < 2$ and $d'(s, t) < 2M$, *i.e.*, s and t are properly connected after the change. We use $p'(s, t)$ to denote a shortest path between s and t after the change. Let u' be the vertex with the highest rank in all shortest paths between s and t after the change, and $u' \in p'(s, t)$.

Before the maintenance, let x be the vertex farthest to u' along $p'(u', b_k)$ such that u' is a hub of x, and the corresponding label-contained distance value is $d'(u', x)$. Let y be the neighbor of x along $p'(u', b_k)$ such that u' is not a hub of y, or u' is a hub of y but the corresponding label-contained distance value is not $d'(u', y)$.

If u' is a hub of y but the corresponding label-contained distance value is not $d'(u', y)$ before the maintenance, then we must have $d'(u', y) > d(u', y)$. In this case, BatchM4GST-Delete must call $SPREAD_1$ to set $L(y)[u']$ to ∞, and then call $SPREAD_2$ and $SPREAD_3$ to re-spread hub u' from x to y, and ultimately to s, along $p'(s, t)$, *i.e.*, to generate a new label $(u', d'(u', s)) \in L(s)$.

If u' is not a hub of y before the maintenance, then there must be a vertex z such that $z \in C(u') \cap C(y)$, $r(z) > r(u')$, and z is in a shortest path between u' and y, and $u' \in PPR[y, z]$ and $y \in PPR[u', z]$ before the maintenance. Since u' is the vertex with the highest rank in all shortest paths between u' and y after the change, z is not in a shortest path between u' and y after the change. To meet this condition, either $L(u')[z]$ or $L(y)[z]$ increases after the graph change. Thus, BatchM4GST-Delete must call $SPREAD_1$ to set either $L(u')[z]$ or $L(y)[z]$ to ∞. In either case, using the above PPR, BatchM4GST-Delete performs $SPREAD_2$ and $SPREAD_3$ to re-spread hub u' from x to y, and ultimately to s, along $p'(s, t)$, *i.e.*, to generate a new label $(u', d'(u', s)) \in L(s)$.

Therefore, in either case, we have $(u', d'(u', s)) \in L(s)$, and similarly $(u', d'(u', t)) \in L(t)$ after the maintenance. Hence, for every pair of properly connected vertices v_i and v_j such that $|\{v_i, v_j\} \cap D| < 2$, there is a common hub vertex $u \in C(v_i) \cap C(v_j)$ on a shortest path between v_i and v_j, *i.e.*, the maintained set of labels by BatchM4GST-Delete still satisfies the GST-customized 2-hop cover constraint. This theorem holds. □

S2. COMPLEXITIES OF ALGORITHMS

A. Complexities of HL4GST

The time complexity of the proposed HL4GST is

$$O\big(|E| \cdot \delta \cdot (\delta + \log |V|)\big)$$

in a single thread environment, where δ is the average number of labels associated with each vertex. The details are as follows. First, the labeling process in Lines 1-14 takes $O(|E| \cdot \delta \cdot (\delta + \log |V|))$ time. The reason is that, for each label inserted into $L'(v)$ in Line 8, it may insert $|N(v)|$ elements into Q in Line 12, and for each element in Q, it takes $O(\log |V|)$ time to pop it out in Line 5 (*e.g.*, using Fibonacci heap [1]) and $O(\delta)$ time to query a distance in Line 6. Second, the sorting process in Lines 15-16 takes $O(|V| \cdot \delta \cdot \log \delta)$ time. Since we generally have $|E| \gg |V|$, the above complexity is covered by that of the labeling process. Third, the cleaning process in Lines 17-21 takes $O(|V| \cdot \delta^2)$ time, given that a distance query that costs $O(\delta)$ is required for cleaning each label. The cost of $O(|V| \cdot \delta^2)$ is also covered by that of the labeling process.

B. Complexities of BatchM4GST-Insert

The proposed BatchM4GST-Insert has a time complexity of

$$O\big(|E_c| \cdot \delta^2 + \Upsilon \cdot (\log \Upsilon + d_a \cdot \delta)\big)$$

in a single thread environment, where Υ is the number of update labels, and d_a is the average degree of vertices that are associated with these labels. The details are as follows. First, populating CL in Lines 1-18 takes $O(|E_c| \cdot \delta^2)$ time, since each distance query in Lines 5 and 13 costs $O(\delta)$.

Second, $DIFFUSE$ takes $O(\Upsilon \cdot (\log \Upsilon + d_a \cdot \delta))$ time. The reason is that, since $O(|CL|) = O(\Upsilon)$, the initialization steps in Lines 21-23 takes $O(\Upsilon)$ time. Moreover, $DIFFUSE$ pops $O(\Upsilon)$ elements out of the priority queue. Each pop operation takes $O(\log \Upsilon)$ times. After each pop, it searches $O(d_a)$ neighbors, and a distance query that costs $O(\delta)$ may be conducted in each search. On the other hand, due to the cost of PPR, the space complexity of BatchM4GST-Insert is $O(|E| \cdot \delta)$.

C. Complexities of BatchM4GST-Delete

The proposed BatchM4GST-Delete has a time complexity of

$$O\big(|E_c| \cdot \delta + \Upsilon \cdot \big(\log \Upsilon + d_a \cdot \delta + \kappa \cdot (d_a + \delta)\big)\big)$$

in a single thread environment, where κ is the average number of PPR elements of each vertex-hub pair. The details are as follows. First, it pushes labels into AL_1 in Lines 2-8 in $O(|E_c| \cdot \delta)$ time. Then, it performs $SPREAD_1$ in $O(\Upsilon \cdot d_a)$ time, since there are $O(\Upsilon)$ labels deactivated, and each deactivation is followed by $O(d_a)$ neighbor searches. Subsequently, it performs $SPREAD_2$ in $O(\Upsilon \cdot \kappa \cdot (d_a + \delta))$ time, since for each of $O(\Upsilon)$ tuples in AL_2, it checks $O(\kappa)$ PPR elements in Line 19, while checking each PPR element takes $O(d_a + \delta)$ time, due to the cost of $O(d_a)$ for computing $d1(x,t)$ and $d1(t,x)$ in Lines 21 and 28, and the cost of $O(\delta)$ for querying distances in Lines 23 and 30. After that, similar to $DIFFUSE$ in BatchM4GST-Insert, it performs $SPREAD_3$ in $O(\Upsilon \cdot (\log \Upsilon + d_a \cdot \delta))$ time, given that $O(|AL_3|) = O(\Upsilon)$. In the end, due to the cost of PPR, the space complexity of BatchM4GST-Delete is $O(|E| \cdot \delta)$.

D. Comparison between the proposed BatchM4GST and state-of-the-art methods

As discussed above, the proposed batch-friendly label maintenance framework: BatchM4GST contains a new integrated label update process that takes

$$O\big(\Upsilon \cdot (\log \Upsilon + d_a \cdot \delta)\big)$$

time. In comparison, the label update process in state-of-the-art algorithms [2–4] takes

$$O\big(\Upsilon \cdot d_a^2 \cdot \delta\big)$$

time. Since we generally have

$$d_a^2 \cdot \delta \gg \log \Upsilon + d_a \cdot \delta \tag{S1}$$

in practice, BatchM4GST obtains a smaller time cost than state-of-the-art algorithms [2–4]. We present details of the label update process in state-of-the-art algorithms as follows.

We take DecreaseAsyn in [2] as an example to show the label update process in state-of-the-art algorithms. We refer to DecreaseAsyn as InsertAsyn in the main experiments. It maintains 2-hop labels after an edge weight decrease or an edge insertion, and can be parallelly implemented in batch cases [4]. IncreaseAsyn in [2] that deals with an edge weight increase or an edge deletion has a similar label update process with DecreaseAsyn. These two algorithms, including their parallel versions [4], are state-of-the-art 2-hop label maintenance methods.

We show the pseudo code of DecreaseAsyn as Algorithm S1. Suppose that the weight of an edge $(a,b) \in E$ decreases from $w_0(a,b)$ to $w_1(a,b)$. The idea of DecreaseAsyn is to update all outdated label-contained distance values that correspond to paths that pass through the old (a,b), first for labels of a and b, and then neighbors of a and b, and then neighbors of neighbors, *etc.*

DecreaseAsyn first initializes two empty sets: CL^c and CL^n (Line 1). It uses CL^c to record new labels of a and b in Lines 2-17. DecreaseAsyn uses CL^c to record new labels of b as follows. For each $(v, d_{va}) \in L(a)$, if $r(v) \geq r(b)$ (Line 3), which means that v could be a hub of b, then it checks whether the queried distance between v and b is larger than $d_{va} + w_1(a,b)$. If it is, then we can generate a new label $(v, d_{va} + w_1(a,b)) \in L(b)$. Thus, it sets $L(b)[v] = d_{va} + w_1(a,b)$, and pushes $(b, v, d_{va} + w_1)$ into CL^c (Line 5), for iteratively updating more labels in later processes. Otherwise, it conducts the above step when $v \in C(b)$ & $L(b)[v] > d_{va} + w_1(a,b)$ (Line 7), and then inserts v into $PPR[b, h_c]$, and also inserts b into $PPR[v, h_c]$, where h_c is the common hub responsible for the queried distance between v and b. The condition that $v \in C(b)$ & $L(b)[v] > d_{va} + w_1(a,b)$ means that v is already a hub of b, and $L(b)[v]$ is larger than, but should be decreased to, $d_{va} + w_1(a,b)$. This step is not in [2], but is necessary for combining DecreaseAsyn and IncreaseAsyn together to deal with fully dynamic cases where edge weights may alternately increase and decrease. After that, it uses CL^c to record new labels of a similarly (Lines 10-17).

Algorithm S1. The DecreaseAsyn algorithm

Input: the original $G_0(V, E_0, w_0)$, the updated $G_1(V, E_1, w_1)$, (a, b), L, PPR
Output: the maintained L and PPR

1: $CL^c = CL^n = \emptyset$
2: **for** each label $(v, d_{va}) \in L(a)$ **do**
3:   **if** $r(v) \geq r(b)$ **then**
4:     **if** $Query(v, b, L) > d_{va} + w_1(a, b)$ **then**
5:       $L(b)[v] = d_{va} + w_1(a, b), CL^c.push((b, v, d_{va} + w_1(a, b)))$
6:     **else**
7:       **if** $v \in C(b)$ & $L(b)[v] > d_{va} + w_1(a, b)$ **then**
8:         $L(b)[v] = d_{va} + w_1(a, b), CL^c.push((b, v, d_{va} + w_1(a, b)))$
9:       $PPR[b, h_c].push(v), PPR[v, h_c].push(b)$
10: **for** each label $(v, d_{vb}) \in L(b)$ **do**
11:   **if** $r(v) \geq r(a)$ **then**
12:     **if** $Query(v, a, L) > d_{vb} + w_1(a, b)$ **then**
13:       $L(a)[v] = d_{vb} + w_1(a, b), CL^c.push((a, v, d_{vb} + w_1(a, b)))$
14:     **else**
15:       **if** $v \in C(a)$ & $L(a)[v] > d_{vb} + w_1(a, b)$ **then**
16:         $L(a)[v] = d_{vb} + w_1(a, b), CL^c.push((a, v, d_{vb} + w_1(a, b)))$
17:       $PPR[a, h_c].push(v), PPR[v, h_c].push(a)$
18: **while** $CL^c \neq \emptyset$ **do** $ProDecrease(CL^c, CL^n), CL^c = CL^n, CL^n = \emptyset$
19: Return L and PPR

Procedure $ProDecrease(CL^c, CL^n)$
20: **for** each $(u, v, d_u) \in CL^c$ **do**
21:   **for** each $u_n \in N(u)$ **do**
22:     **if** $r(v) > r(u_n)$ **then**
23:       **if** $Query(v, u_n, L) > d_{new} = d_u + w_1(u, u_n)$ **then**
24:         $L(u_n)[v] = d_{new}, CL^n.push((u_n, v, d_{new}))$
25:       **else**
26:         **if** $v \in C(u_n)$ & $L(u_n)[v] > d_{new}$ **then**
27:           $L(u_n)[v] = d_{new}, CL^n.push((u_n, v, d_{new}))$
28:         $PPR[u_n, h_c].push(v), PPR[v, h_c].push(u_n)$

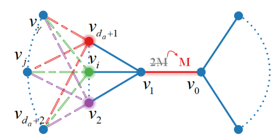

Fig. S2. An example to show the label update process in DecreaseAsyn.

Subsequently, while $CL^c \neq \emptyset$, DecreaseAsyn iteratively uses the $ProDecrease$ procedure to update more labels (Line 18). CL^c and CL^n are the sets of updated labels in the last and current iterations, respectively. To perform these iterations, it sets $CL^c = CL^n$ and $CL^n = \emptyset$ after using $ProDecrease$ in each iteration. In $ProDecrease$, for each $(u, v, d_u) \in CL^c$ (Line 20), it checks each neighbor u_n of u (Line 21). If $r(v) > r(u_n)$, which means that v could be a hub of u_n, then it checks whether the queried distance between v and u_n is larger than $d_{new} = d_u + w_1(u, u_n)$ (Line 23). If it is, then we can generate a new label $(v, d_{new}) \in L(u_n)$. Thus, it updates $L(u_n)[v] = d_{new}$, and pushes (u_n, v, d_{new}) into CL^n (Line 24). Otherwise, it conducts the above step when $v \in C(u_n)$ & $L(u_n)[v] > d_{new}$, and then inserts v into $PPR[u_n, h_c]$, and also inserts u_n into $PPR[v, h_c]$ (Line 28), where h_c is the common hub responsible for the queried distance between v and u_n. The update of PPR is for maintaining 2-hop labels in later edge weight increase or edge deletion cases. In the end, DecreaseAsyn returns the updated L and PPR (Line 19).

After a change, DecreaseAsyn first updates labels of a and b, and then updates labels of neighbors of a and b, and then neighbors of neighbors etc., until no label needs to be updated. The above label update process, *i.e.*, the iterative call of $ProDecrease$, takes $O(\Upsilon \cdot d_a^2 \cdot \delta)$ time. The details are as follows. First, note that, the above label update process updates a label-contained distance value $L(x)[v]$ by spreading hub v from a or b to x in a breadth first search way. This process performs a distance relaxation in Lines 23-24 for each searched edge. As a result, this process may update a label-contained distance value $L(x)[v]$ at most $O(d_a)$ times in the breadth first search process. Thus, this process could perform $O(\Upsilon \cdot d_a)$ label update operations. Each label update operation in an iterative call of $ProDecrease$ induces $O(d_a)$ distance queries in the next iterative call of $ProDecrease$. Since each distance query takes $O(\delta)$ time [5, 6], the above label update process takes $O(\Upsilon \cdot d_a^2 \cdot \delta)$ time. We show an example as follows.

Consider the graph in Figure S2, where $M \gg \Upsilon \gg d_a^2$; $w_0(v_0, v_1) = 2M$; $w_0(v_1, v_i) = 1$ for each $i \in [2, d_a + 1]$; there is a simple path between v_i and v_j for every pair of $i \in [2, d_a + 1]$ and $j \in [d_a + 2, \Upsilon]$, and this path contains $i - 1$ edges and has a total weight of $d_a - i + 2$. Suppose that the weight of (v_0, v_1) decreases from $2M$ to M. DecreaseAsyn maintains labels as follows. Initially, it updates $L(v_1)[v_0] = M$ and $L(v_i)[v_0] = M + 1$ for each $i \in [2, d_a + 1]$. Subsequently, for a certain $j \in [d_a + 2, \Upsilon]$, it sequentially updates $L(v_j)[v_0] = M + 1 + d_a - i + 2$ through the path between v_i

and v_j for each $i \in [2, d_a + 1]$. As a result, they update label-contained distance values $O(\Upsilon \cdot d_a)$ times. Since each label update in an iterative call of $ProDecrease$ induces $O(d_a)$ distance queries in the next iterative call, DecreaseAsyn conducts $O(\Upsilon \cdot d_a^2)$ distance queries. Since each distance query takes $O(\delta)$ time, the label update process in DecreaseAsyn costs $O(\Upsilon \cdot d_a^2 \cdot \delta)$. In comparison, as discussed before, the integrated label update process in the proposed BatchM4GST has a smaller time cost of $O(\Upsilon \cdot (\log \Upsilon + d_a \cdot \delta))$.

REFERENCES FOR THE SUPPLEMENT

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